Prepared in cooperation with the Honolulu Board of Water Supply

Groundwater and Surface-Water Interactions in the He‘eia Watershed, O‘ahu, Hawai‘i—Insights from Analysis of Historical Data and Numerical Groundwater-Model Simulations

Scientific Investigations Report 2024–5020

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

Cover. Photograph of the upper reaches of Heʻeia Stream, Heʻeia watershed, Oʻahu, Hawaiʻi. Photograph by Scot Izuka, USGS.

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Geographic Names

Geographic names in this report are largely consistent with the U.S. Geological Survey (USGS) Board on Geographic Names (http://geonames.usgs.gov/), including the use of the ‘okina (‘) and kahakō (¯) diacritical marks in Hawaiian names. The diacritical marks are not used, however, in anglicized derivations from Hawaiian names (for example, the ‘okina appears in the name “Hawai‘i” but not in the derivation “Hawaiian”), or where a place name appears without the diacritical marks in an established name or title in a cited reference or database (for example, well names in this report appear as they do in state and local government databases). Names of geologic formations and features are consistent with the State of Hawai‘i geologic map by Sherrod and others (2021).

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
gallon (gal)	3.785	liter (L)
million gallons (Mgal)	3,785	cubic meter (m^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per day (ft^3/d)	0.02832	cubic meter per day (m^3/d)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)

Other useful conversion:

Cubic feet per second (ft^3/s) can be converted to million gallons per day (Mgal/d) as Mgal/d = (ft^3/s) x 0.6464

Datum

Vertical coordinate information is referenced to local mean sea level.

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

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

Abbreviations

BFI	Base-Flow Index, a program for computing base flow from streamgage data
ENSO	El Niño-Southern Oscillation
GHCN	Global Historical Climatology Network
HBWS	Honolulu Board of Water Supply
IIFS	Interim instream-flow standard
MODFLOW-2005	Computer program for creating and executing numerical models of groundwater flow
SWI2	Seawater Intrusion Package, a package in MODFLOW-2005
NCEI	National Centers for Environmental Information
NWIS	National Water Information System (http://dx.doi.org/10.5066/F7P55KJN)
PIWSC	Pacific Islands Water Science Center
SKN	State key number (for rain gages)
USGS	U.S. Geological Survey

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Abstract

He‘eia and ‘Ioleka‘a Streams in the He‘eia watershed on O‘ahu, Hawai‘i, receive substantial discharge from dike-impounded groundwater. Previous studies indicated that groundwater withdrawals from the watershed affect streamflow. Resource managers and users seek information that can be used to balance the needs of competing uses of groundwater and streamflow in the watershed.

In this study, analyses of historical streamflow and withdrawal data indicate that when groundwater withdrawals from Haiku Tunnel (a groundwater development tunnel built in the 1940s in the watershed) of 1.73–1.87 million gallons per day (Mgal/d) were introduced in the first few decades of the tunnel's operation, base flow at a gage on He‘eia Stream decreased by 1.37–1.40 Mgal/d. Changes in rainfall during this period were not sufficient to account for the changes in base flow. The tunnel withdrawal also affected ‘Ioleka‘a Stream, but the effect was less. In the 1980s, average withdrawal from the tunnel decreased by 0.73–1.00 Mgal/d and base flow at the He‘eia streamgage increased by 0.15–0.21 Mgal/d; a concurrent rainfall increase may partly account for the base-flow increase. Withdrawal from another well (Haiku well) starting in the late 1980s had a much smaller effect than the tunnel did on flow at the He‘eia streamgage.

Numerical groundwater-model simulations indicate that shutting down withdrawals from Haiku Tunnel and Haiku well would increase base flows in streams inside and outside of the He‘eia watershed. Simulated shutdown of 0.35 Mgal/d withdrawal from Haiku well caused base flow of streams in the He‘eia watershed to increase by 0.09 Mgal/d or 26 percent of the withdrawal reduction, and shutdown of 0.60 Mgal/d withdrawal from Haiku Tunnel caused base flow of streams within the watershed to increase by 0.12 Mgal/d or 20 percent of withdrawal reduction. Shutdown of a combined 0.95 Mgal/d withdrawal from the tunnel and well caused base flow of streams within the watershed to increase by 0.22 Mgal/d or 23 percent of the withdrawal reduction.

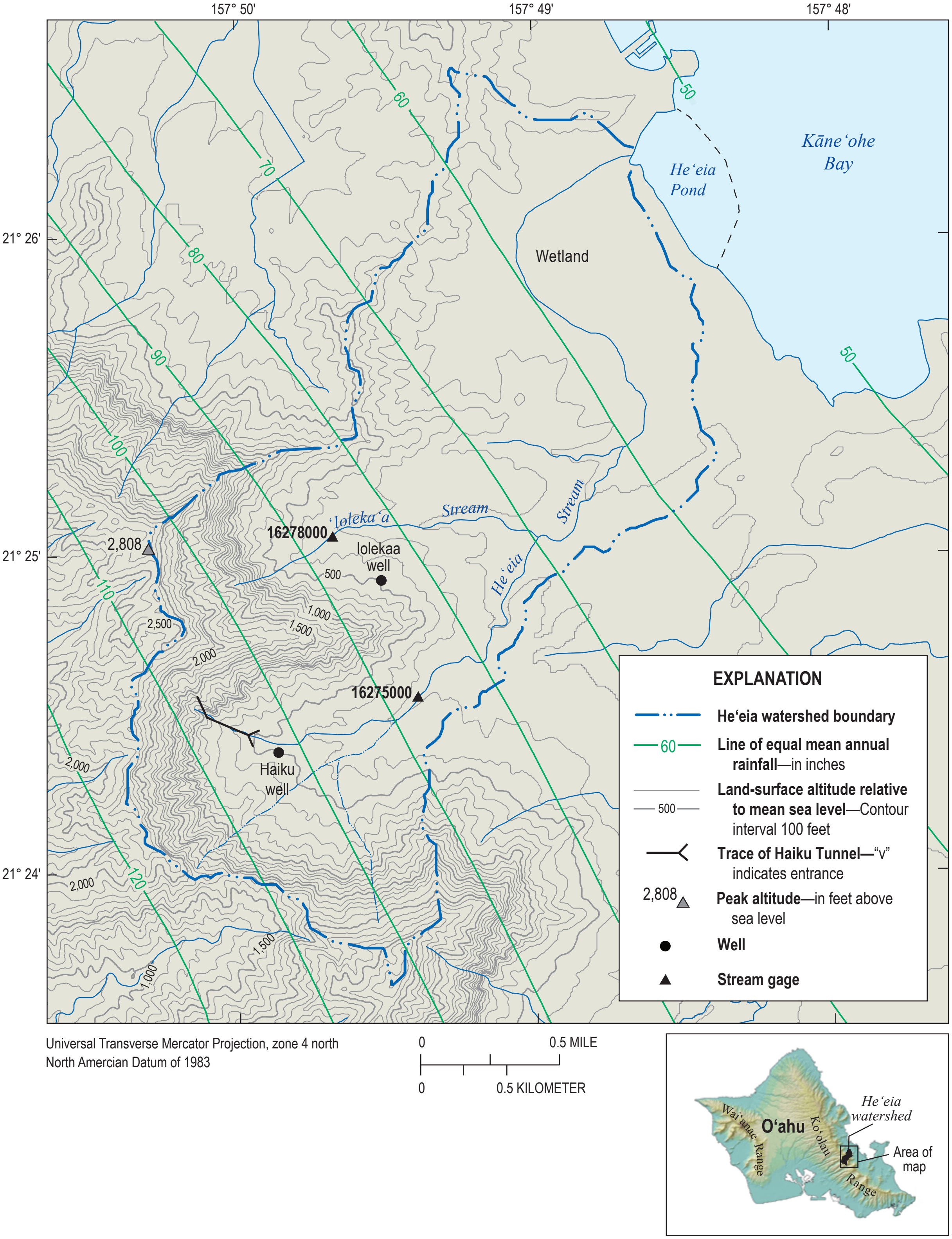
The model simulations and analyses of streamflow data demonstrate that, climate changes notwithstanding, reducing or shutting down withdrawal from Haiku Tunnel has not in the past, and will not in the future, restore base flow to predevelopment rates. The nearly pristine condition that existed prior to the construction of the Haiku Tunnel no longer exists because other large-producing tunnels and wells near the He‘eia watershed have since begun withdrawing water from the same dike-impounded aquifer. Reduction or shutdown of withdrawals from the wells and tunnel in the He‘eia watershed cannot restore streamflow to predevelopment rates if withdrawals from all other wells and tunnels continue.

Introduction

The He‘eia watershed encompasses an area of about 3.4 mi^2 on the windward flank of the Ko‘olau Range on O‘ahu, Hawai‘i (fig. 1). The watershed includes Ha‘ikū and ‘Ioleka‘a Valleys, He‘eia and ‘Ioleka‘a Streams, and a wetland. Water from streams in the watershed is used for agriculture, and freshwater discharge at the mouth of the stream supports Hawaiian aquaculture at the He‘eia Pond, a walled offshore fishpond (loko i‘a kuapā). The Honolulu Board of Water Supply (HBWS) withdraws groundwater from several sources in the watershed, including Haiku Tunnel, Haiku well, and Iolekaa well, which provide water for domestic and public-trust uses.

Low-flow statistics for gages on He‘eia (16275000) and ‘Ioleka‘a (16278000) Streams (fig. 1) indicate that the streams receive substantial base flow (Cheng, 2016). Base flow is the flow that persists in a stream even during periods when direct runoff of water from rainfall is absent. In hydrographs from gages where groundwater discharge to streams is substantial (such as those in the He‘eia watershed), surface runoff appears as peaks and recessions superimposed on base flow (fig. 2). If anthropogenic sources of surface runoff (for example, irrigation) are negligible, base flow is an indicator of groundwater discharge to the stream. Results from previous studies (for example, Hirashima, 1962, 1971; Takasaki and others, 1969; Izuka and others, 1993) indicated that withdrawals from Haiku Tunnel have caused reductions in stream base flow.

The State of Hawai‘i Commission on Water Resource Management is in the process of preparing interim instream-flow standards (IIFS) for He‘eia Stream (fig. 1). The IIFS seeks to establish minimum streamflows while balancing the needs



Universal Transverse Mercator Projection, zone 4 north
North Amercian Datum of 1983

Figure 1. Map of the He‘eia watershed, O‘ahu, Hawai‘i. Altitude contours generated from U.S. Geological Survey (USGS) digital-elevation-model data. Streams and coastline modified from USGS National Hydrography Dataset. Lines showing distribution of mean annual rainfall were generated using data from Giambelluca and others (2013).

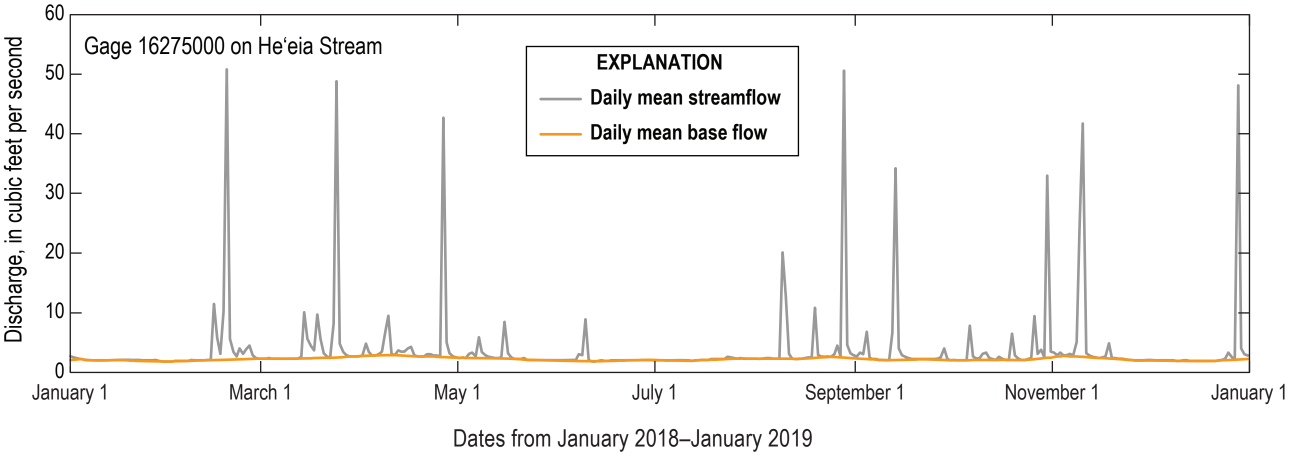


Figure 2. Hydrograph showing daily mean streamflow and base flow at gage 16275000 on He'eia Stream from 2018 to 2019. Streamflow at this location has substantial base flow from groundwater discharge. Streamflow peaks above base flow are from direct runoff during and immediately following rain events. Streamflow data from U.S. Geological Survey (2022).

of competing uses, including instream uses such as ecological, cultural, and aesthetic uses, and off-stream uses such as stream diversions for agriculture and groundwater withdrawals that support communities but affect streamflow.

The objective of this study is to advance understanding of the hydrology of the He‘eia watershed with a focus on the connection between groundwater withdrawals and stream base flow. The study examines existing streamflow, groundwater withdrawal, and rainfall data for indications of historical effects of groundwater withdrawals on base flow within the watershed. The study also uses numerical groundwater-model simulations to assess how streamflow within and beyond the watershed may change if groundwater withdrawals in the watershed are reduced. The results of this study inform management decisions that seek to balance the needs of competing beneficial uses.

Setting

O‘ahu has an area of 597 mi^2 and is the third-largest island in Hawai‘i. The island has two prominent mountains, the Wai‘anae Range (peak altitude 4,025 ft) and Ko‘olau Range (peak altitude 3,105 ft) (fig. 1). The He‘eia watershed occupies an area of about 3.4 mi^2 on the northeast flank of the Ko‘olau Range. The watershed is bounded by steep cliffs on the southwest and descends into a low-lying wetland in the northeast. Streams draining the watershed empty into the He‘eia Pond and Kāne‘ohe Bay, which opens to the Pacific Ocean.

The Hawaiian Islands lie in the trade-wind belt of the tropical North Pacific Ocean. Most areas of the islands have mild temperatures, moderate humidity, and prevailing northeasterly trade winds (Giambelluca and Schroeder, 1998). Precipitation distribution is influenced by the orographic effect—prevailing northeasterly trade winds blow against the mountain slopes, forcing air to rise and cool and water to condense. On O‘ahu, average annual rainfall is higher in areas on northeast-facing (windward) slopes (which includes the He‘eia watershed) and the crest of the Ko‘olau Range, and lower in leeward areas. The orographic effect also results in steep rainfall gradients—in the He‘eia watershed, rainfall ranges from about 50 in/yr near the coast to more than 100 in/yr at the ridge crests (Giambelluca and others, 2013) (fig. 1). In addition, occasional convective storms unrelated to the orographic effect can bring rain to any part of the island (Giambelluca and others, 2013). Rainfall on O‘ahu can vary seasonally, although the seasonal pattern differs by location (Giambelluca and others, 1986, 2013). In general, rainfall is lower in May to September and higher in October to April, but in the He‘eia watershed and similar sites on the windward flank of the Ko‘olau Range where the orographic effect predominates, rainfall tends to be more evenly distributed through the year (Giambelluca and others, 2013). Precipitation also varies with multi-year cycles linked to ocean/atmosphere climate cycles such as the El-Niño-Southern Oscillation (ENSO) (Chu and Chen, 2005). Annual rainfall totals on O‘ahu are typically lower during the El Niño phase of ENSO (Giambelluca and others, 2013).

The Wai‘anae and Ko‘olau Ranges are the erosional remnants of two shield volcanoes that built the subaerial part of O‘ahu (a third shield volcano is buried by the Wai‘anae volcano and its rocks do not crop out above sea level) (Sinton and others, 2014; Sherrod and others, 2021). The volcanoes are built of thousands of thin lava flows that typically form highly permeable aquifers, with horizontal hydraulic conductivity values of hundreds to tens of thousands of feet per day (Soroos, 1973; Lau and Mink, 2006; Rotzoll and El-Kadi, 2008).

The He‘eia watershed lies in a part of the Ko‘olau Range where dikes have intruded the lava flows of the shield volcano (Stearns and Vaksvik, 1935; Takasaki and Mink, 1985; Walker, 1987). The hydrology of dike-intruded areas can be conceptualized as a system of compartments in which groundwater is impounded in compartments of high-permeability lava flows between the low-permeability dikes; this setting is known as dike-impounded groundwater (Takasaki and Mink, 1985; Izuka and others 2018, Izuka and Rotzoll, 2023) (fig. 3). Groundwater can accumulate to high altitudes in the dike compartments; in contrast, water levels in most dike-free high-permeability lava-flow aquifers on O‘ahu are less than a few tens of feet above sea level (Izuka and others, 2018). Groundwater can flow from one compartment to another—a small amount of water seeps through the dike rock but most of the water probably flows over the top or around the dikes (Macdonald and others, 1960).

In the He‘eia watershed, where erosion has breached the dike compartments, groundwater discharges to springs, streams, the wetland, and the ocean (Izuka and others, 1993). In some parts of the watershed, especially near the coast and in the wetland, groundwater passes through sediments and rocks from late-stage (rejuvenated) volcanism before emerging at the surface. Groundwater discharge maintains substantial base flow in the streams that drain the He‘eia watershed. The base flow varies with groundwater storage in the dike compartments, which in turn varies with rainfall and withdrawals from wells and the tunnels in and near the watershed. Oki (2004) and Bassiouni and Oki (2013) found statistically significant downward trends in the base flow of streams on Kaua‘i, O‘ahu, Moloka‘i, and Maui for the period from 1913 to 2008, and listed decreasing groundwater storage as one of the possible causes.

Most dikes in the Ko‘olau Range are aligned in a northwest-southeast trend that corresponds to the trend of the ancient rift zone of the Ko‘olau shield volcano (fig. 4). The alignment results in preferential groundwater flow in the direction of the dikes (Hirashima, 1962; Takasaki and Mink, 1985; Walker, 1987).

Groundwater Development—Groundwater in dike-impounded-groundwater settings is developed by wells that penetrate the dike compartments vertically from above and by tunnels driven horizontally into the dike compartments (fig. 3*B*). Withdrawing water from the dike-impounded-groundwater setting causes water-level declines and reductions in groundwater discharge to streams, springs, wetlands, and the ocean (Izuka and others, 2018).

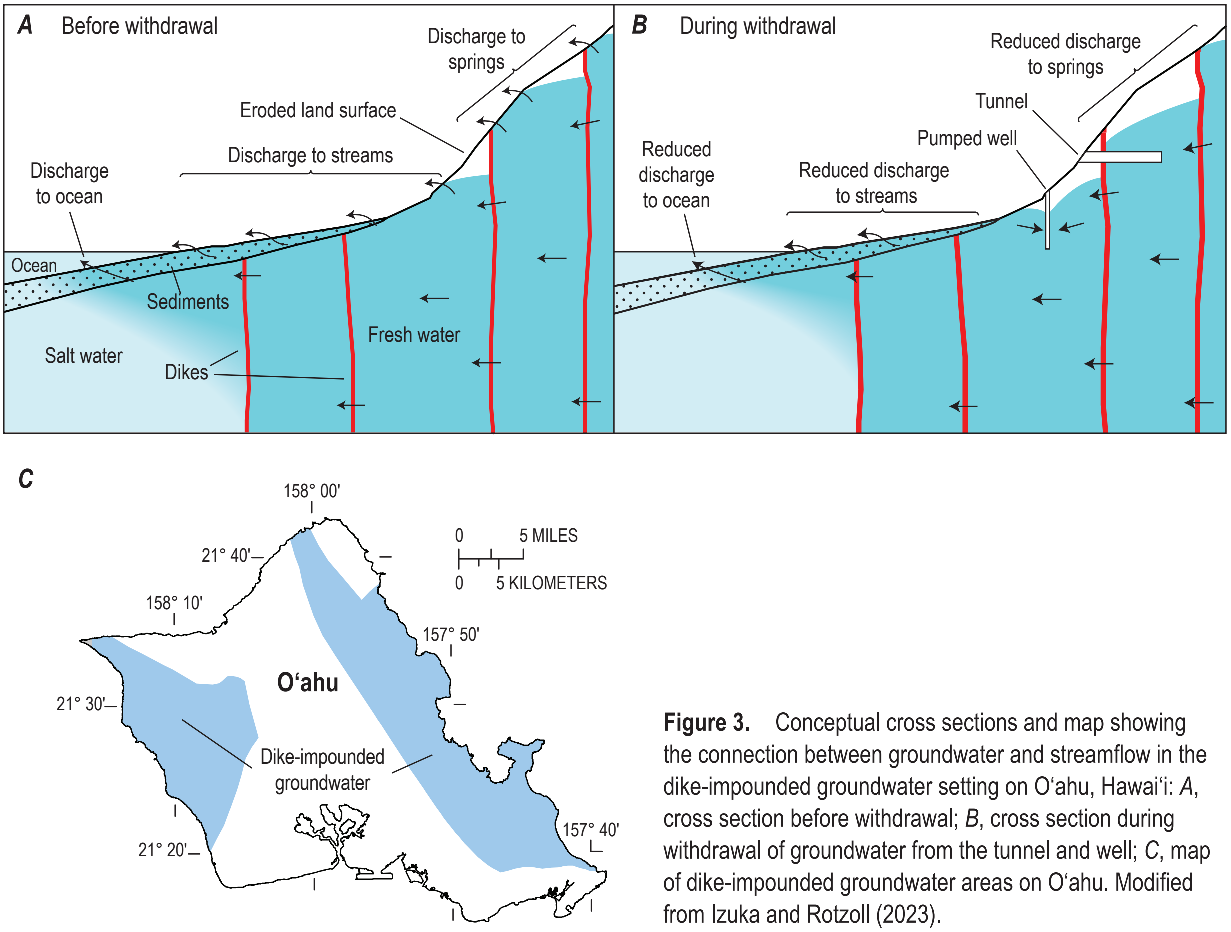
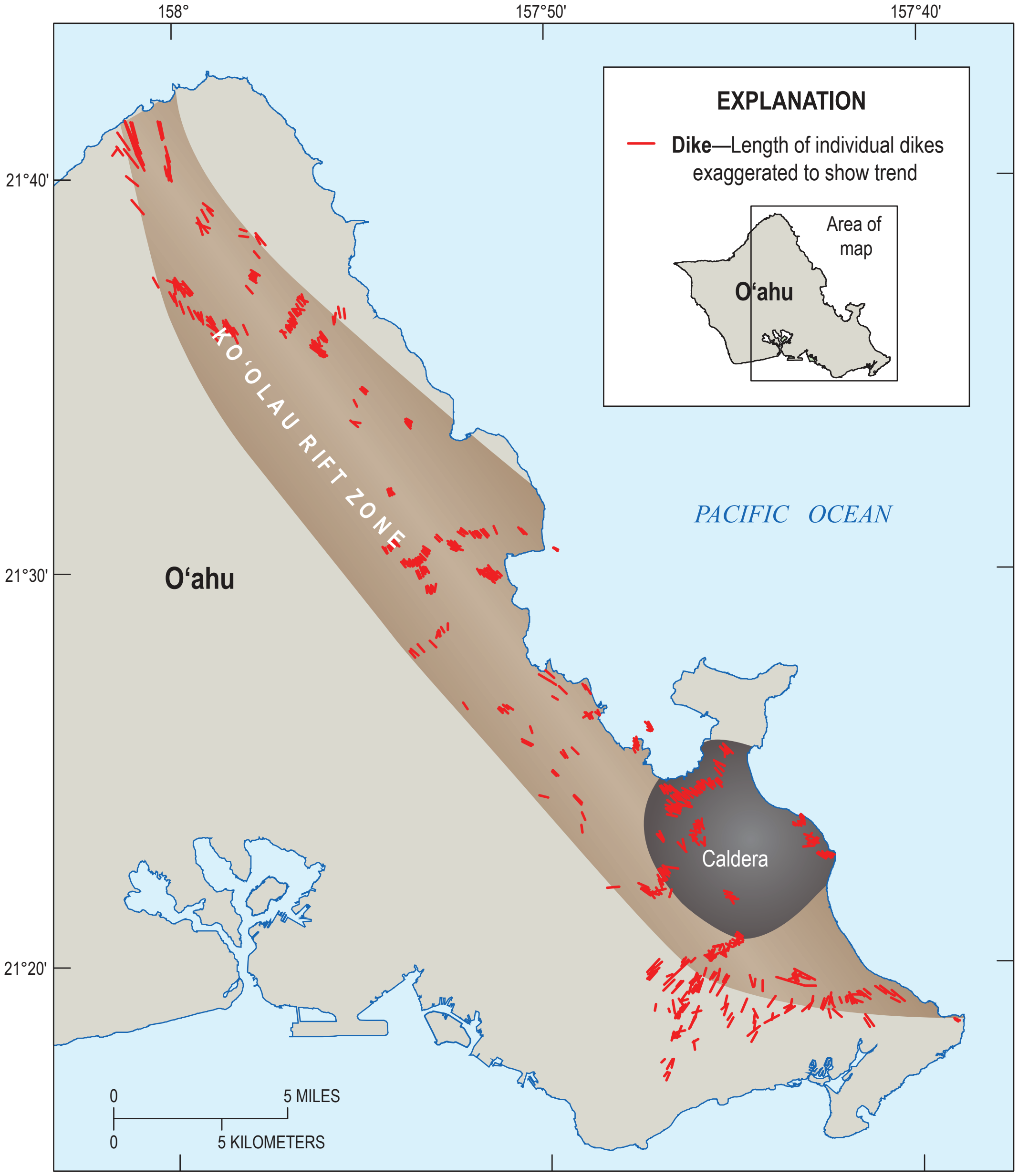


Figure 3. Conceptual cross sections and map showing the connection between groundwater and streamflow in the dike-impounded groundwater setting on O‘ahu, Hawai‘i: *A*, cross section before withdrawal; *B*, cross section during withdrawal of groundwater from the tunnel and well; *C*, map of dike-impounded groundwater areas on O‘ahu. Modified from Izuka and Rotzoll (2023).

Groundwater in the dike-impounded setting flows from areas of inflow (recharge areas) to areas of outflow (natural discharge to springs, streams, wetlands, and submarine seeps, as well as artificial withdrawals at wells and tunnels). Prior to groundwater withdrawals, the system can be assumed to be in a near-steady-state condition (fig. 3*A*) in which the long-term average inflow rate balances the long-term average outflow rate. Introduction of withdrawals from wells and tunnels upsets the predevelopment balance and the system transitions gradually toward a new balance—water withdrawn from wells and tunnels initially comes from storage, but as time progresses, more and more of the withdrawal is compensated by reductions in groundwater discharge to springs, streams, wetlands, and seepage to the ocean. If withdrawals are not excessive, the system will eventually achieve a new steady-state condition, storage reduction will cease, and the outflow rate (natural outflow plus artificial withdrawals) will again equal the inflow rate (fig. 3*B*). Stated alternatively, any amount of groundwater withdrawal from wells and tunnels will be compensated, in the long term, by an equivalent reduction of natural groundwater discharge to springs, streams, wetlands, or the ocean (assuming recharge remains constant). How far the impact of groundwater withdrawals will spread depends on the withdrawal rates and their locations relative to geologic structures, distribution of hydraulic properties, and sites of natural discharge



North American Datum 1983, Universal Transverse Mercator projection, zone 4N

Figure 4. Map of dikes and interpreted locations of the rift zone and caldera of the Koʻolau volcano, Oʻahu, Hawaiʻi. Modified from Izuka and others, 2018.

such as springs, streams, wetlands, and the ocean (Izuka and Rotzoll, 2023).

If withdrawals are subsequently reduced or halted, a new transient condition will begin during which storage and natural discharge will gradually increase. The system will transition to a new equilibrium in which storage will stop increasing and natural groundwater discharge to streams, springs, wetlands, and the ocean will have increased by an amount equal to the reduction of withdrawal. The amount of time needed to achieve steady state depends on recharge, groundwater flow rates, and aquifer properties. Changes in withdrawals sometimes occur so frequently that steady state cannot be achieved. Variations in precipitation can also cause short-term imbalances between inflows and outflows.

In the He‘eia watershed, dike-impounded groundwater is developed by Haiku Tunnel (State well number 3-2450-001) and several wells, including Haiku well (State well number 3-2450-002) and Iolekaa well (State well number 3-2549-001) (fig. 1). Construction of Haiku Tunnel started in the middle of 1940 and was completed in late 1940 or early 1941. The tunnel penetrated 1,300 ft northwest into the base of a cliff in the Ko‘olau Range at an altitude of about 550 ft (fig. 1). During construction and likely for a few weeks thereafter, as much as 11 Mgal/d or 17 ft^3/s of groundwater flowed freely from the tunnel as it penetrated dike compartments; this groundwater was initially discharged to He‘eia Stream and can be seen in streamgage data (Hirashima, 1962, 1963). Bulkheads and pipes were subsequently installed to control tunnel flow and distribute the water for use. Dewatering of dike compartments during construction reduced flows in springs and streams in the He‘eia watershed (Hirashima, 1971; Takasaki and others, 1969). Continued withdrawals from Haiku Tunnel also affected flows in steams beyond the watershed boundary (Hirashima, 1962, 1963; Takasaki and others, 1969). During the period of data furnished by the HBWS (January 1944 through December 2021), withdrawal from Haiku Tunnel averaged 1.31 Mgal/d (2.03 ft^3/s).

Haiku well was drilled from an altitude of 497 ft to a depth of 600 ft in 1981. The well penetrated alluvium and younger volcanic deposits before penetrating 350 ft of lava flows of the Ko‘olau shield volcano (Izuka and others, 1993). The water-level altitude after the well was completed was 327 ft; a water level at such a high altitude within 2.5 mi of the coast is consistent with the dike-impounded groundwater setting. Haiku well is located downslope from Haiku Tunnel (fig. 1), and the well's water level is lower than the altitude of the tunnel; these facts indicate that the well and tunnel tap different dike compartments. During the period of data furnished by the HBWS (January 1989 through December 2021), withdrawal from Haiku well averaged 0.31 Mgal/d (0.48 ft^3/s).

Iolekaa well was drilled from an altitude of 485 ft to a depth of 241 ft in 1966 (VTN Pacific, 1983) in an outcrop of lava flows of the Ko‘olau volcano. The water-level altitude at the time the well was completed was 321 ft, which is consistent with the dike-impounded-groundwater setting. The Iolekaa well's lower water level and location downslope from Haiku Tunnel indicate that it develops water from a different dike compartment than the one tapped by Haiku Tunnel. Whether Haiku and Iolekaa wells tap the same dike compartment is not known—the wells have similar water-level altitudes, and their location relative to each other and to the trend of dikes in the Ko‘olau Range do not eliminate the possibility that the wells tap the same compartment. However, withdrawal from the Iolekaa well is much smaller than the withdrawals from Haiku well and Haiku Tunnel—in the period of data furnished by the HBWS (May 1985 through December 2021), withdrawal from the Iolekaa well averaged only 0.07 Mgal/d (0.11 ft^3/s).

Analyses of Historical Data

This study used base-flow-separation and flow-duration analyses of historical streamgage records to assess the groundwater-discharge (base-flow) component of streams in the He‘eia watershed. Results of these analyses were compared to historical data on groundwater withdrawal to look for correspondence with changes in withdrawal and changes in base flow. Fluctuations in rainfall can also cause variations in groundwater storage and groundwater discharge to streams because groundwater ultimately originates as rainfall. This study also examined rainfall data to assess whether observed base-flow changes were linked to rainfall fluctuations rather than groundwater withdrawals.

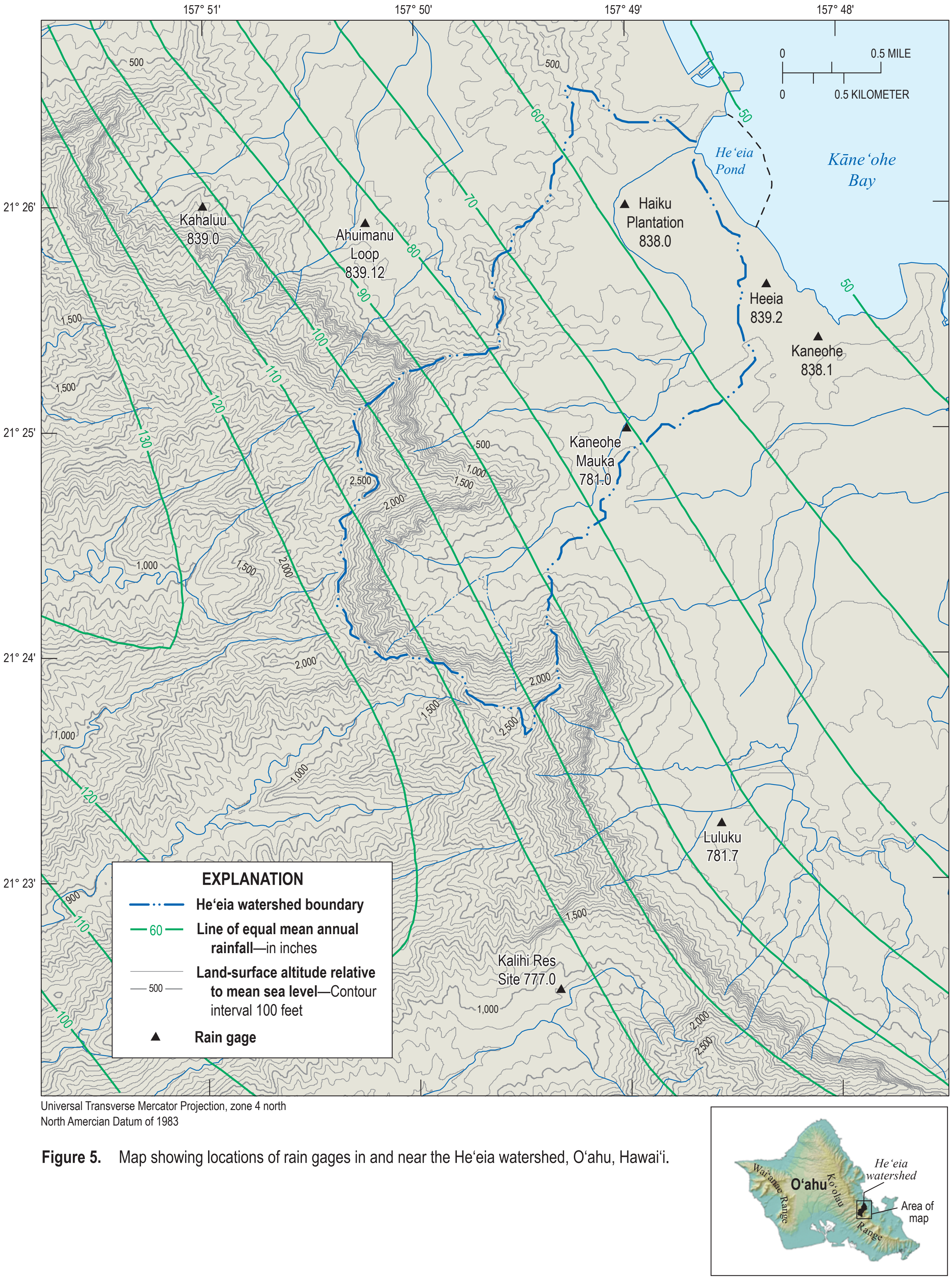
Data Sources

Groundwater withdrawal—Monthly groundwater-withdrawal data for Haiku Tunnel, Haiku well, and Iolekaa well were furnished by HBWS. Because withdrawal from Iolekaa well is much less than the withdrawals from Haiku Tunnel and Haiku well (see the "Setting" section, above), the withdrawal from Iolekaa well is not considered in the analyses of this report.

Streamflow—This study analyzed daily mean streamflow data from the USGS National Water Information System (NWIS) (U.S. Geological Survey, 2022, http://dx.doi.org/10.5066/F7P55KJN). USGS streamgage 16275000 (fig. 1), with a drainage area 1.0 mi^2, has monitored flow in He'eia Stream since 1914, although its record has multi-year data gaps from September 30, 1919 to July 12, 1939 and from November 1, 1977 to September 30, 1982. At the time of this study, 16275000 was still in operation, but analyses for this study included only approved data up to September 30, 2021. USGS streamgage 16278000, with a drainage area 0.3 mi^2, monitored flow on ‘Ioleka‘a Stream from 1940 to 1970; its record is complete in this span except for three gaps of one to two months in 1942–1943. The combined drainage areas of gages 16275000 and 16278000 constitute about 38 percent of the watershed.

Rainfall—Fluctuations in rainfall can cause variations in groundwater recharge, storage, and discharge to streams. Extended periods with little rainfall can result in reduced groundwater discharge to streams whereas periods with substantial rainfall can lead to increased groundwater discharge to streams. Consideration of rainfall data is therefore needed to separate base-flow variations linked to rainfall fluctuations from base-flow variations caused by withdrawal of groundwater from the tunnel and wells.

For this report, daily precipitation data from eight rain gages in and near the He‘eia watershed (fig. 5) were obtained from the National Centers for Environmental Information (NCEI) Global Historical Climatology Network (GHCN)-Daily database (NCEI, 2022). The names of rain gages used in this report are simplified



Universal Transverse Mercator Projection, zone 4 north
North Amercian Datum of 1983

Figure 5. Map showing locations of rain gages in and near the He‘eia watershed, O‘ahu, Hawai‘i.

versions of the names in the GHCN-Daily database and include the State Key Number (SKN). An apparent error in the location data for Heeia 839.2 in the GHCN-Daily database was corrected using the geographical reference data for the station from the Rainfall Atlas of Hawai‘i (Giambelluca and others, 2013).

Eight rain gages within or near the watershed have data from the period of interest in this study (1930 through 2001). All but one have records that are incomplete or do not span the whole period of interest, and some are at lower altitudes where rainfall is less than it is in the upper watershed monitored by streamgages 16275000 and 16278000 (fig. 5). Only the Kalihi Res Site 777.0 rain gage had a complete dataset spanning the period of interest in this study. The gage lies about 1.3 mi south of the southern boundary of the watershed and is within the region where rainfall is dominated by the orographic effect similar to the study area. To avoid spatial vagaries in short-term rainfall, data from this gage were used primarily as an indicator of changes in average rainfall for multi-year subperiods in this study. For assessing shorter-term (daily or monthly) rainfall variations, total streamflow was used as a surrogate indicator. Comparison of data from within the watershed indicates that total streamflow peaks coincide closely with rainfall events (fig. 6). Although the streamflow peaks cannot be converted to rainfall, the peaks can be used as a graphical indicator of rainfall frequency for periods when streamflow data are available.

Flow-Duration Analysis

Flow-duration curves are a convenient way to compare base-flow differences for selected periods, such as before and during withdrawals. Flow-duration curves are cumulative-frequency curves that show the percentage of time specified discharges at a location on a stream were equaled or exceeded during a given period (Searcy, 1959) (fig. 7). Plotted on a log-probability graph, flow-duration curves from gages where streamflow has a substantial groundwater component tend to have a low-flow end (right side) that is less steep than the high-flow end (left side). In contrast, curves from gages on reaches without a substantial groundwater component tend to have a monotonic slope from high- to low-flow ends of the graph or a low-flow end that is steeper than the high-flow end. To ensure all seasons are represented equally, many flow-duration curves (including the ones discussed here) are computed on the basis of full water years. A water year is a 12-month period starting October 1 and ending September 30, and named for the calendar year in which it ends. Partial water years are excluded from the analysis.

Izuka and others (1993) constructed flow-duration curves from daily mean streamflow recorded at the USGS gage 16275000 on He‘eia Stream for three periods representing three different stages in the history of tunnel and well construction in the watershed: (1) before construction of Haiku Tunnel, (2) after construction of Haiku Tunnel but before construction of Haiku well, and (3) after construction of Haiku Tunnel and Haiku well (fig. 8*A*). For discussion in this report, these stages are referred to as Period I, Period II, and Period III, respectively. Izuka and others (1993) concluded that the lower base flow in Period II was caused at least in part by the introduction of withdrawals from Haiku Tunnel (difference in precipitation was not enough to account for the decrease in base flow). However, their inferences on the apparent increase in base flow between Period II and Period III were limited because only two years of data were available for Period III at the time of their study.

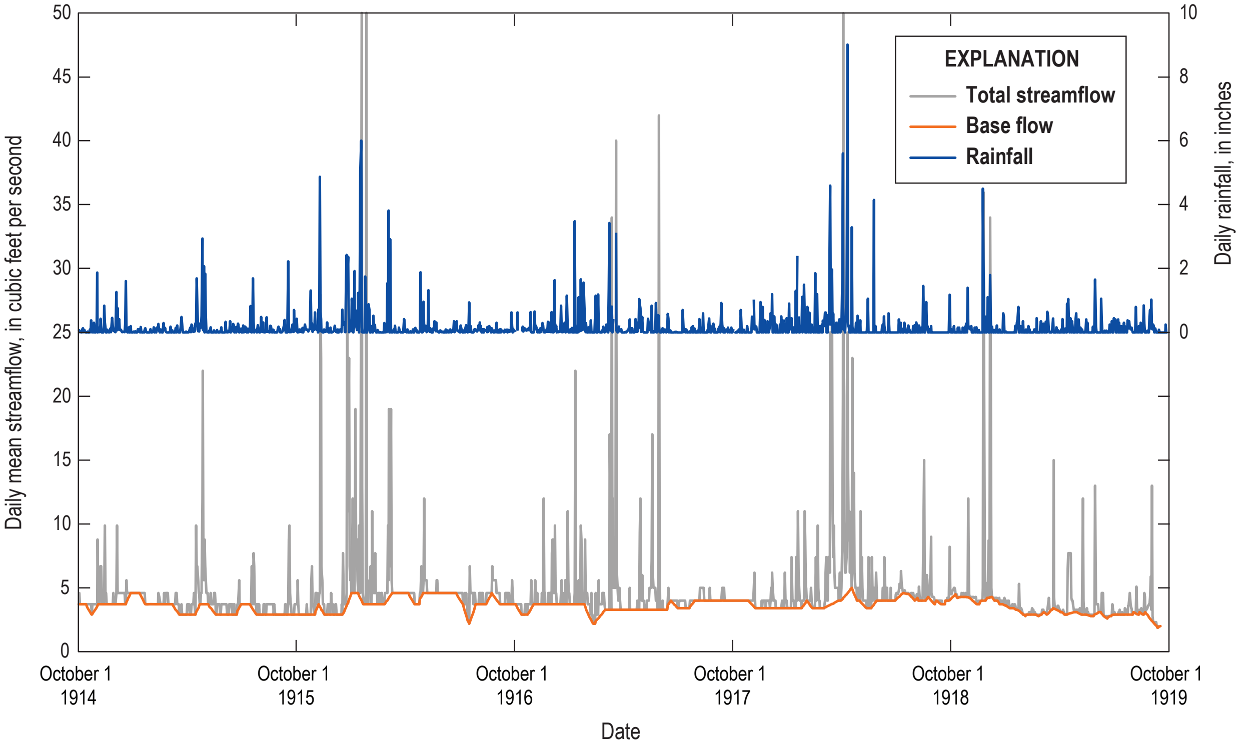


Figure 6. Graph comparing flow at gage 16275000 on He‘eia Stream and rainfall at rain gage He‘eia SKN 839.20, O‘ahu, Hawai‘i. Streamflow data from USGS (2022); rainfall data from National Centers for Environmental Information (2022).

In this study, the flow-duration curves of Izuka and others (1993) were reconstructed with additional data through September 30, 2020. Period IIIa (fig. 8*B*) includes data through water-year 2020, whereas data for Periods I and II in this study are the same as they are in the analysis of Izuka and others (1993). Except for minor differences related to differences in the plotting methods, the flow-duration curves in this study (fig. 8*B*) are generally similar to those of Izuka and others (1993) (fig. 8*A*). The flow-duration curves from this study indicate that base flow at gage 16275000 was highest in Period I, lowest in Period II, and intermediate in Period IIIa, although base flows in Period IIIa in this study are lower than they were for Period III from the study of Izuka and others (1993). The apparent increase in base flow between Periods II and IIIa coincide with a reduction in groundwater withdrawals; the relation between base flows and withdrawals is discussed further in the section "Changes in Base Flow Relative to Changes in Withdrawal."

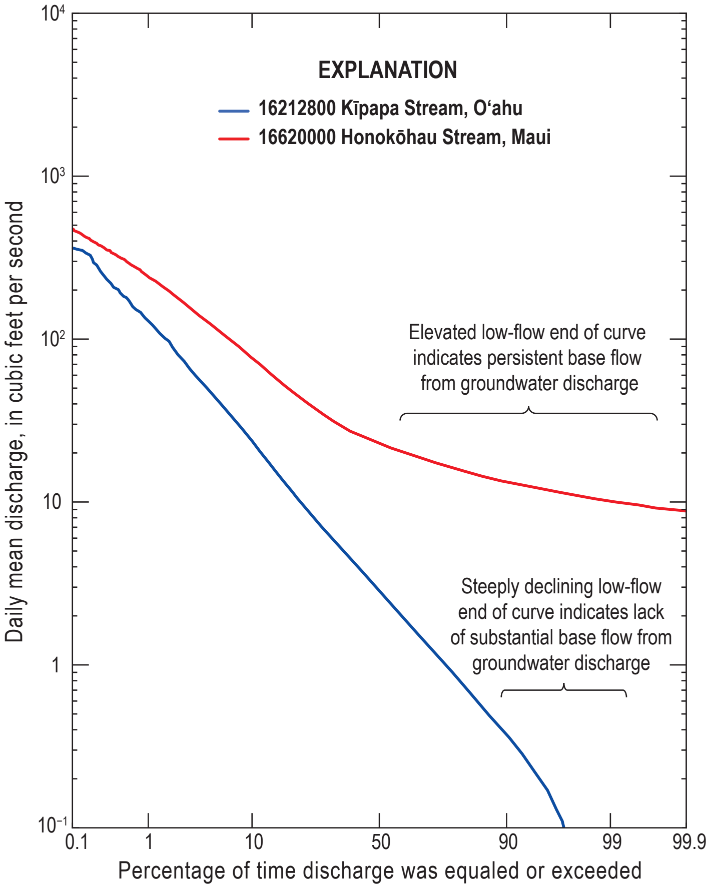


Figure 7. Example flow-duration curves from a gage on a stream reach that receives no groundwater discharge (blue line), and a gage on a stream reach that receives substantial groundwater discharge (red line). Gages are on streams on O‘ahu and Maui, Hawai‘i. Modified from Izuka and others (2018).

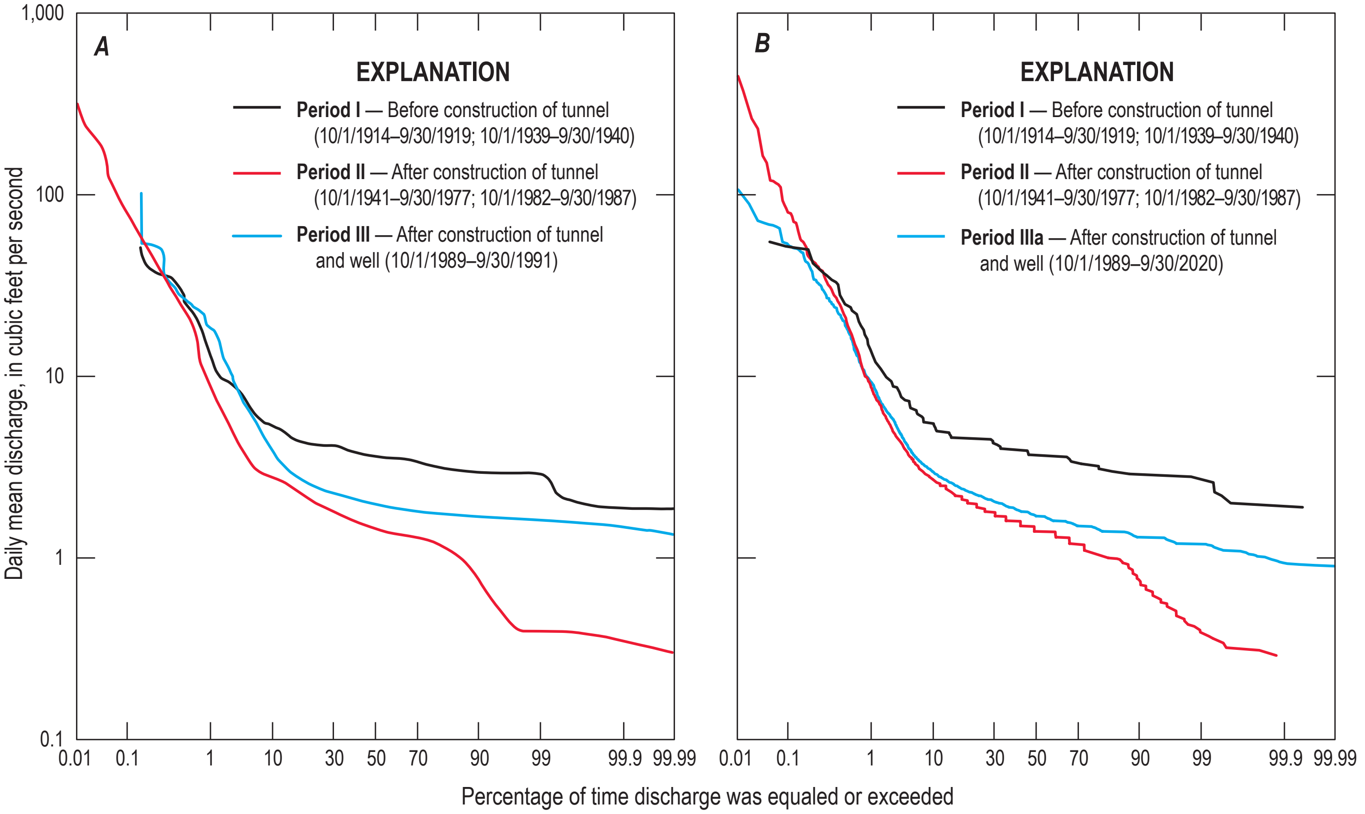


Figure 8. Flow-duration curves for selected periods from streamgage 16275000 on He‘eia Stream, O‘ahu, Hawai‘i. *A*, Curves using data through 1991, redrafted from Izuka and others (1993). *B*, Curves recomputed in this study using data through water-year 2020.

Base-Flow Separation

Base flow can be isolated from the hydrograph of a streamgage to study temporal variations in groundwater discharge to streams, such as variations linked to groundwater withdrawals. In this study, the standard Base-Flow Index (BFI) base-flow-separation program (Wahl and Wahl, 1995), available in the USGS Groundwater Toolbox (Barlow and others, 2015), was used to determine base flow from the daily mean streamflow data from gages 16275000 on He‘eia Stream and 16278000 on ‘Ioleka‘a Stream in the He‘eia watershed (fig. 1). The daily streamflow data from NWIS (U.S. Geological Survey, 2022, http://dx.doi.org/10.5066/F7P55KJN) were analyzed using a partition window (the *N* parameter required by BFI) of 5 days and a turning-point test factor (the *f* parameter required by BFI) of 0.9.

Barlow and others (2015) discussed two key assumptions about the data used in base-flow-separation analysis: (1) the data are unaffected by reservoirs or snowpack that can release water at rates that can be mistaken for base flow and (2) the data reflect contributions from two natural sources, such as direct runoff from rainfall and groundwater discharge. No reservoirs or snowpack exist above gages 16275000 and 16278000, and (as discussed above) streams throughout the dike-impounded groundwater areas of the Ko‘olau Range have a substantial groundwater-discharge component on which direct runoff from rainfall is superimposed. Other guidance discussed by Barlow and others (2015) relates to using base-flow separation to estimate water-budget components (such as groundwater recharge); these assumptions are not relevant to this study, where base-flow-separation analysis is used to eliminate direct runoff so that the patterns of base-flow variation over time are readily apparent and can be assessed in relation to variations in groundwater withdrawal.

Figure 9 compares variations in base flows measured at the gages with variations in withdrawal from Haiku Tunnel from 1940 through 1971 (before construction of Haiku well). Prior to the start of tunnel construction in 1940, base flow at gage 16275000 on He‘eia Stream (fig. 1) was about 3 to 4 ft^3/s (2 to 3 Mgal/d) (fig. 9*A*). During tunnel construction in 1940–1941, groundwater flowing freely from penetrated dike compartments was released into He‘eia Stream, causing a sharp artificial rise in base flow at gage 16275000. The base-flow data indicate that this artificial discharge to the stream ceased sometime in 1941, after which the base flow at 16275000 began a declining trend despite having frequent total-streamflow peaks that indicate frequent

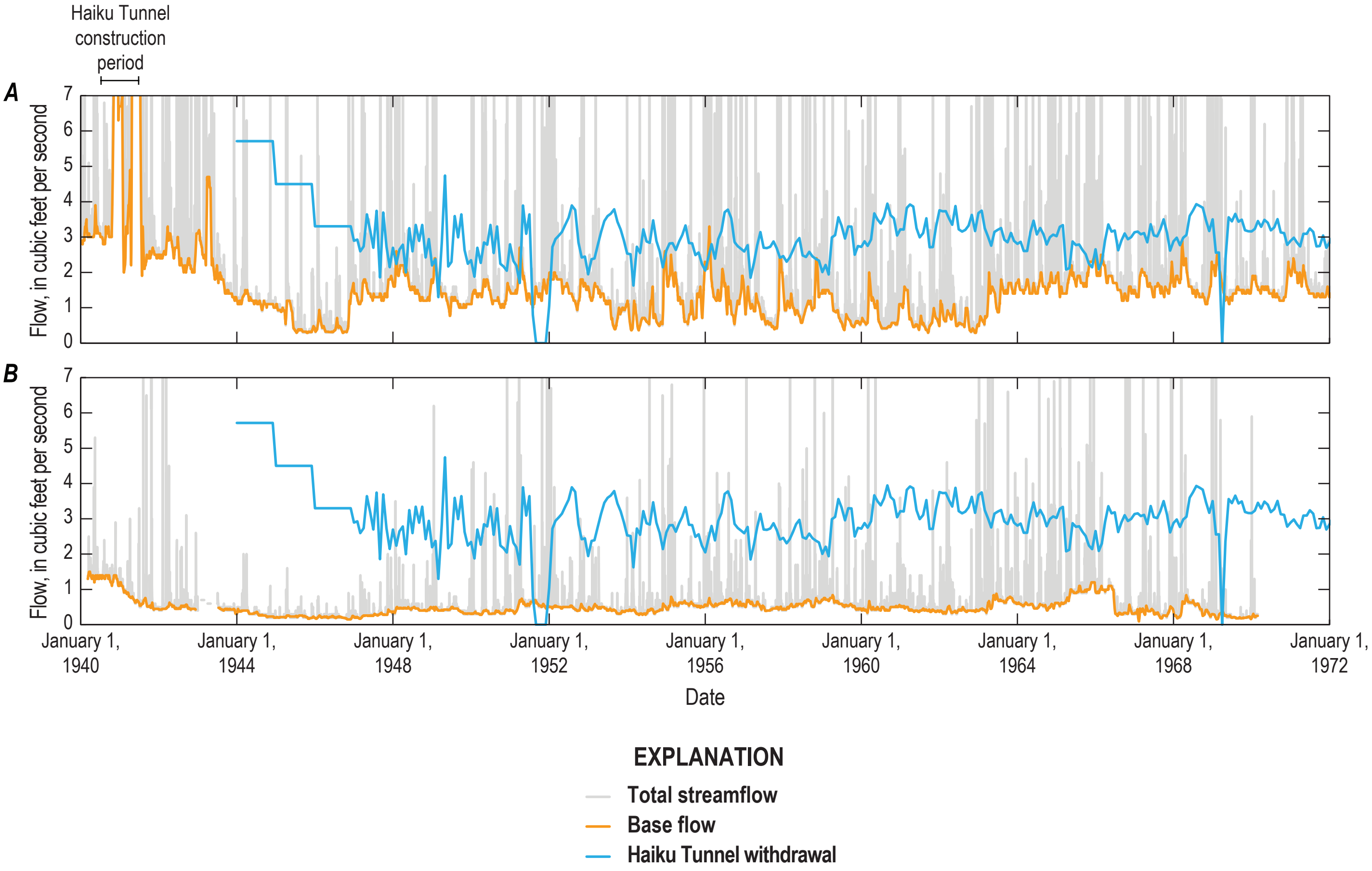


Figure 9. Graphs showing daily mean base flow and total streamflow from 1940 through 1971 at (*A*) gage 16275000 on He‘eia Stream and (*B*) 16278000 on ‘Ioleka‘a Stream. Concurrent monthly groundwater withdrawal from Haiku Tunnel is shown for comparison (monthly values are plotted on the first day of each month). Streamflow data from U.S. Geological Survey (2022); withdrawal data furnished by the Honolulu Board of Water Supply.

rain. The declining trend continued into the start of the period of available withdrawal data for Haiku Tunnel. In the first decades of withdrawal from the tunnel, base flow fluctuated but on average was lower than it was before the tunnel was built. Also after tunnel construction, base flow generally corresponded inversely with withdrawal—base flow typically was lower when withdrawal was high—although variations in rainfall frequency probably caused some base-flow fluctuation.

No water was artificially released into ‘Ioleka‘a stream during construction of Haiku Tunnel in 1940–1941, so base flow at gage 16278000 on ‘Ioleka‘a Stream (figs. 1, 9*B*) does not show an artificial rise analogous to that evident at gage 16275000 on He‘eia Stream. However, base flow at gage 16278000 on ‘Ioleka‘a Stream shows a decrease of about 0.8 ft^3/s (0.5 Mgal/d), coinciding with the time of dike-compartment dewatering during tunnel construction in 1940. The decline continued through 1941, despite a period of frequent direct runoff from rainfall, and into the start of the period of available Haiku Tunnel withdrawal data.

Figure 10 is similar to figure 9*A* in comparing variations in base flow at gage 16275000 on He‘eia Stream to groundwater withdrawals, but the data in figure 10 extend through 2020 and include the period when withdrawal from Haiku well started. The data indicate that through much of the first three decades of its operation, withdrawal from Haiku Tunnel averaged about 2.9 ft^3/s (1.9 Mgal/d). Tunnel withdrawal began a decreasing trend in the 1970s and by the early 1980s had declined to about 1.8 ft^3/s (1.2 Mgal/d).

Withdrawal data for Haiku well starts in 1989 with values of less than 0.1 ft^3/s (fig. 10). Withdrawal rose sharply to about 1.0 ft^3/s (0.7 Mgal/d) in 1990, then declined to about 0.7 ft^3/s (0.5 Mgal/d) in 1991. Withdrawal declined gradually to about 0.5 ft^3/s (0.3 Mgal/d) by 2016 and was shut down for a period between 2016 and 2021 before resuming at about 0.5 ft^3/s (0.3 Mgal/d). Correspondence between variations in base flow and Haiku well withdrawals is not as readily apparent as the correspondence between variations in base flow and Haiku Tunnel withdrawals. This observation indicates that base flow in stream reaches above the gage were affected less by withdrawal from Haiku well than by withdrawal from Haiku Tunnel, which is consistent with the conceptualization that Haiku Tunnel and Haiku well tap different dike compartments. The effect of Haiku well on ‘Ioleka‘a Stream is unknown because gage 16278000 was discontinued before Haiku well was built.

Changes in Base Flow Relative to Changes in Withdrawal

Comparison of base-flow changes to withdrawal changes from the flow-duration and base-flow-separation analyses can be used to assess the overall effect of withdrawals on streams in the He‘eia watershed. If the periods from the analysis represent steady-state conditions, then the sum of all changes in groundwater discharge (including base flow) should balance the changes in withdrawal. However, the periods may include non-steady transitions from one withdrawal condition to another and non-steady variations in rainfall. Furthermore, the base-flow changes indicated by the analyses may be less than the withdrawal rate because the analyses reflect only the impact on groundwater discharge to stream reaches above gage 16275000 on He‘eia Stream, not to all reaches or the ocean or wetlands potentially affected by withdrawals. Even so, comparison of long-term average base-flow changes to withdrawal

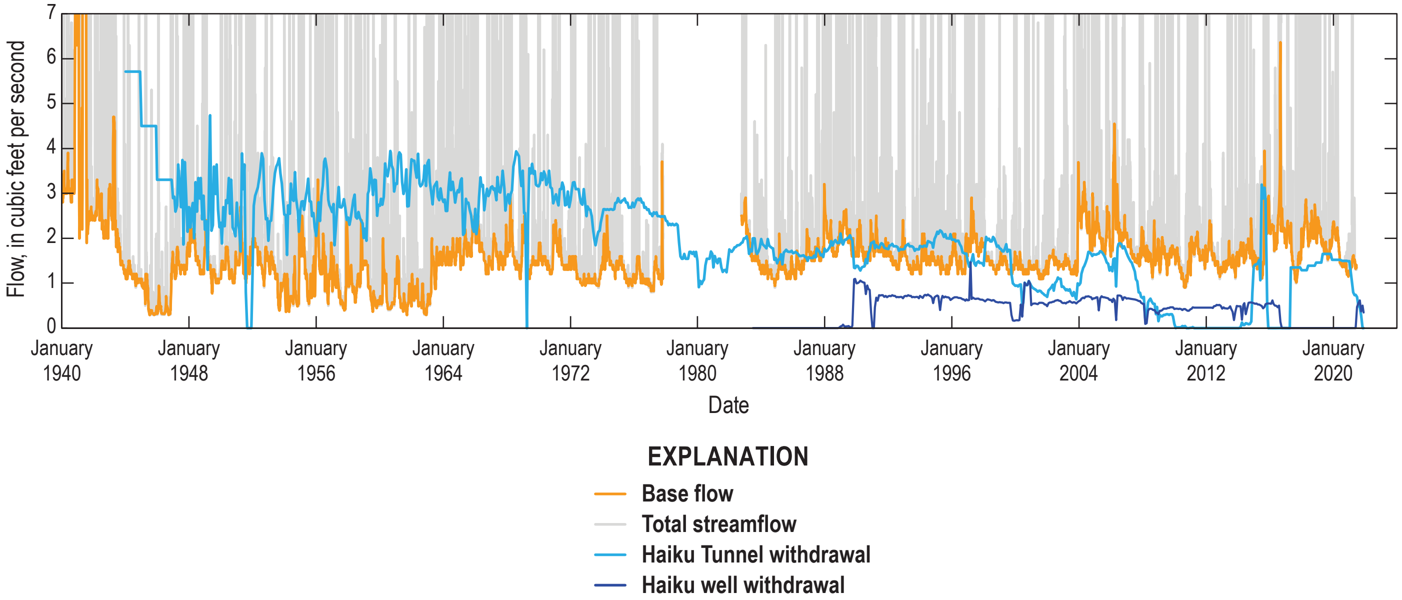


Figure 10. Graph showing daily mean base flow and total streamflow from 1940 to 2021 at gage 16275000 on He‘eia Stream and concurrent monthly groundwater withdrawal from Haiku Tunnel and Haiku well (monthly withdrawal values are plotted on the first day of each month). Streamflow data from U.S. Geological Survey (2022); withdrawal data furnished by the Honolulu Board of Water Supply.

changes can be used to quantify the general effect of historical withdrawals on stream reaches above gage 16275000, provided no presumption is made that the quantities represent true steady state.

Periods Used in the Flow-Duration Analysis—Base-flow differences among Periods I, II, and IIIa for the flow-duration analysis were assessed relative to groundwater-withdrawal data (tables 1 and 2). The base-flow averages for the periods were determined using data from the base-flow-separation analysis. To address the potential effect of rainfall variations, rainfall averages from the Kalihi Res Site 777.0 gage were also computed for the periods.

Base flow at 16275000 on He‘eia Stream averaged 3.46 ft^3/s (2.24 Mgal/d) in Period I and 1.35 ft^3/s (0.87 Mgal/d) in Period II, indicating a decrease of 2.11 ft^3/s (1.37 Mgal/d) between these periods (tables 1 and 2). The base-flow decrease corresponds with the onset of groundwater withdrawals from Haiku Tunnel in Period II when withdrawal averaged 2.68 ft^3/s (1.73 Mgal/d). Whereas average rainfall for Period II is higher than for Period I and therefore cannot account for the base-flow decrease, the base-flow decrease can be attributed to the withdrawals from Haiku Tunnel in Period II. The decrease in average base flow constitutes 79 percent of the increase in average withdrawal from Haiku Tunnel in Period II.

Base flow for Period IIIa averaged 1.58 ft^3/s (1.02 Mgal/d) (table 1), which indicates an increase of 0.23 ft^3/s (0.15 Mgal/d) relative to Period II (table 2). The base-flow increase coincides with a decrease in withdrawal of 1.55 ft^3/s (1.00 Mgal/d) from Haiku Tunnel. Although Period IIIa includes the onset of withdrawal from Haiku well, the average total withdrawal from Haiku Tunnel and Haiku well decreased by 0.61 Mgal/d (0.95 ft^3/s) between Period II and IIIa.

Rainfall differences cannot account for the increase in base flow because rainfall decreased between Period II and IIIa; thus, the base-flow decrease can be attributed to decreases in groundwater withdrawals. The increase in base flow constitutes 15 percent of the decrease in average withdrawal from Haiku Tunnel. The result indicates that reduction in withdrawal between Periods II and IIIa returned a smaller percentage of the withdrawal to the streams than initiation of withdrawal between Periods I and II took from the streams.

Table 1. Average base flow, withdrawal, and rainfall for periods used in flow-duration analysis of daily mean values for gage 16275000, He‘eia Stream, O‘ahu, Hawai‘i.

[Mgal/d, million gallons per day; ft^3/s, cubic feet per second; in/d, inches per day]

Period	Withdrdawal conditions represented	Period of data analyzed	Average base flow at gage 16275000 on He‘eia Stream[1]		Average withdrawal[2]						Average rainfall[3] (in/d)
					Haiku Tunnel		Haiku well		Haiku Tunnel and well		
			Mgal/d	ft^3/s	Mgal/d	ft^3/s	Mgal/d	ft^3/s	Mgal/d	ft^3/s	
I	Before construction of Haiku Tunnel	October 1914–September 1919; October 1939–September 1940	2.24	3.46	0.00	0.00	0.00	0.00	0.00	0.00	0.30
II	After construction of Haiku Tunnel; before construction of Haiku well	October 1941–September 1977; October 1982–September 1987	0.87	1.35	1.73	2.68	0.00	0.00	1.73	2.68	0.32
IIIa	After construction of Haiku Tunnel and Haiku well	October 1989–September 2020	1.02	1.58	0.73	1.13	0.39	0.60	1.12	1.73	0.27

[1] Computed from results of base-flow separation.

[2] Computed from data furnished by the Honolulu Board of Water Supply.

[3] Computed from data from the Kalihi Res Site 777.0 rain gage (National Centers for Environmental Information, 2022).

Table 2. Differences between periods used in flow-duration analysis of daily mean values for gage 16275000, He‘eia Stream, O‘ahu, Hawai‘i.

[Negative values indicate decrease from earlier peiod to later period. Mgal/d, million gallons per day; ft^3/s, cubic feet per second; in/d, inches per day]

Periods	Average base flow[1]		Average withdrawal[2]						Rainfall[3] (in/d)	Average base flow as a percentage of withdrawal from Haiku Tunnel
			Haiku Tunnel		Haiku well		Haiku Tunnel and well			
	Mgal/d	ft^3/s	Mgal/d	ft^3/s	Mgal/d	ft^3/s	Mgal/d	ft^3/s		
I and II	−1.37	−2.11	1.73	2.68	0.00	0.00	1.73	2.68	0.02	79
II and IIIa	0.15	0.23	−1.00	−1.55	0.39	0.60	−0.61	0.95	−0.05	15

[1] Computed from results of base-flow separation.

[2] Computed from data furnished by the Honolulu Board of Water Supply.

[3] Computed from data from the Kalihi Res Site 777.0 rain gage (National Centers for Environmental Information, 2022).

Periods Selected from the Base-Flow-Separation Analysis—To reduce the possible effects of non-steady conditions that may be encompassed by the periods used in the flow-duration analysis, averages for withdrawal, base flow, and rainfall were computed for selected periods during which withdrawal fluctuated but showed no consistent downward or upward trend. The periods were selected on the basis of withdrawal from Haiku Tunnel only because withdrawals from other wells have substantially less effect on base flow at gage 1627500 (see figure 10 and related discussion above).

The periods include a predevelopment period similar to Period I, plus two periods having withdrawal rates that are substantially different from previous periods (shown by the shaded areas in fig. 11). To use as much data as possible for these periods of steady withdrawal, the periods are not constrained by water years. Although inclusion of incomplete water years has the potential to introduce seasonal bias to the averages, incomplete water years constituted less than 6 percent of any given period, so the effect of seasonal bias will be small. For the purposes of discussion in this report, these periods are identified with upper-case letters A, B, and C (table 3) to distinguish the periods from those used in the flow-duration analysis (Periods I, II, and IIIa). The date ranges for Periods A, B, and C differ from those for Periods I, II, and IIIa and are not constrained by water years, but in general, (1) Period A and Period I represent predevelopment conditions, (2) Period B and Period II represent the time when Haiku Tunnel was operating but Haiku well was not, and (3) Period C and Period IIIa represent the time when Haiku Tunnel and Haiku well were operating simultaneously.

Base flow at 16275000 on He‘eia Stream averaged 3.47 ft^3/s (2.24 Mgal/d) in Period A and 1.30 ft^3/s (0.84 Mgal/d) in Period B, indicating a decrease of 2.17 ft^3/s (1.40 Mgal/d) between Periods A and B (tables 3 and 4). This change represents a 63-percent decrease in base flow. Rainfall was also 0.05 in/d less in Period B than in Period A, but this constitutes a much smaller decrease (16 percent) than the change in base flow. The difference in base flow between Periods A and B is 75 percent of the average withdrawal from Haiku Tunnel (2.89 ft^3/s or 1.87 Mgal/d) in Period B, which is similar to the analogous percentage (79 percent) between Periods I and II from the flow-duration analysis (compare tables 2 and 4).

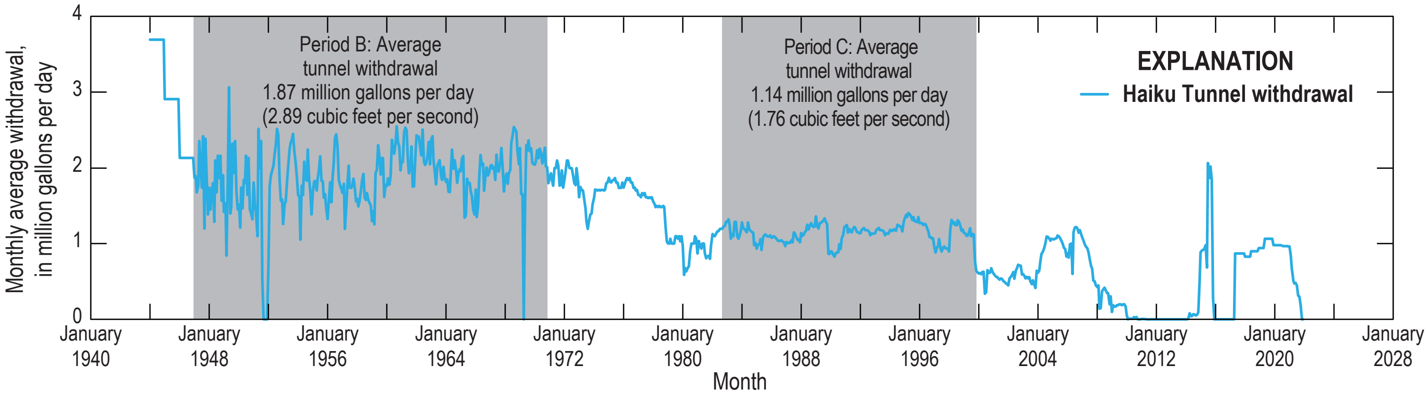


Figure 11. Graph showing monthly groundwater withdrawal from Haiku Tunnel, O‘ahu, Hawai‘i, and averages for selected subperiods during which withdrawal showed no upward or downward trend. Data furnished by the Honolulu Board of Water Supply.

Table 3. Average withdrawal, base flow, and rainfall for selected periods during which withdrawal from Haiku Tunnel, He‘eia watershed, O‘ahu, Hawai‘i, showed no upward or downward trend.

[Mgal/d, million gallons per day; ft^3/s, cubic feet per second; in/d, inches per day]

Period	Period analyzed	Average withdrawal from Haiku Tunnel[1]		Average base flow at gage 16275000 on He‘eia Stream		Average rainfall[2] (in/d)
		Mgal/d	ft^3/s	Mgal/d	ft^3/s	
A	October 1, 1914–September 17, 1919; July 13, 1939–September 30, 1940	0.00	0.00	2.24	3.47	0.31
B	January 1, 1947–September 30, 1970	1.87	2.89	0.84	1.30	0.26
C	October 9, 1982–September 30, 1999	1.14	1.76	1.05	1.62	0.33

[1] Computed from data furnished by the Honolulu Board of Water Supply.

[2] Computed from data from the Kalihi Res Site 777.0 rain gage (National Centers for Environmental Information, 2022).

Table 4. Differences between selected periods during which withdrawal from Haiku Tunnel, He‘eia watershed, O‘ahu, Hawai‘i, showed no upward or downward trend.

[Negative values indicate decrease from earlier period to later period. Mgal/d, million gallons per day; ft^3/s, cubic feet per second; in/d, inches per day]

Periods	Average withdrawal from Haiku Tunnel[1]		Base flow at 16275000, He‘eia Stream			Rainfall[2] (in/d)
	Mgal/d	ft^3/s	Mgal/d	ft^3/s	Percent of withdrawal	
A and B	1.87	2.89	−1.40	−2.17	75	−0.05
B and C	−0.73	−1.13	0.21	0.32	29	0.07

[1] Computed from data furnished by the Honolulu Board of Water Supply.

[2] Computed from data from the Kalihi Res Site 777.0 rain gage (National Centers for Environmental Information, 2022).

Base flow at gage 16275000 was 1.62 ft^3/s (1.05 Mgal/d) in Period C, which is 0.32 ft^3/s (0.21 Mgal/d) greater than it was in Period B (tables 3 and 4). Withdrawal from Haiku Tunnel was 1.13 ft^3/s (0.73 Mgal/d) less in Period C than in Period B. The increase in base flow between Periods B and C is 29 percent of the reduction in average withdrawal. These results indicate that reduction in withdrawal between Periods B and C returned a smaller percentage of the withdrawal to the streams than initiation of withdrawal between Periods A and B took from the streams. The implication is similar to that of the flow-duration analysis, although the percentages differ (compare tables 2 and 4). In addition, rainfall was 0.07 in/d (27 percent) greater in Period C than in Period B (table 4), which may have contributed to the base-flow increase.

Relative Effects of Haiku Tunnel on He‘eia and ‘Ioleka‘a Streams

Comparison of data from gages 16278000 on ‘Ioleka‘a Stream and 16275000 on He‘eia Stream before and after tunnel construction can be used to estimate the relative effect of Haiku Tunnel on reaches of the two streams above their respective gages. The gages operated concurrently for a 234-day period (March 6, 1940 to October 15, 1940) before base flow at 16275000 was artificially altered by discharge of water from the construction of Haiku Tunnel (fig. 9). Although the concurrent period is less than a year, it is the only period of data available from both gages that represent conditions prior to substantial effects from tunnel construction and operation. Period A_{con} (a subset of Period A) in table 5 represents the concurrent pre-tunnel period of the two gages. As in table 4, Period B represents the first few decades of withdrawal from Haiku Tunnel (data from 16278000 is about 2 percent short of the full span of Period B, but the shortfall is negligible).

The change in average base flow between Periods A_{con} and B is −1.78 ft^3/s (−1.15 Mgal/d) at gage 16275000 on He‘eia Stream and −0.87 ft^3/s (−0.56 Mgal/d) at gage 16278000 on ‘Ioleka‘a Stream (table 5). The sum of the change in average base flow for the two stream gages is −2.65 ft^3/s (−1.71 Mgal/d) which is 92 percent of the average withdrawal rate (2.89 ft^3/s or 1.87 Mgal/d) during Period B. Inaccuracies in this analysis may result because base flows during Period B may not have reached steady state with respect to the new tunnel withdrawals, but the inaccuracies are likely small because, as indicated in the timeseries data (figs. 9 and 10), reductions in base flow follow fairly quickly after initiation of withdrawals. Inaccuracies may also result from the short duration of Period A_{con}. The average base flow at gage 16275000, during Period A_{con} (3.08 ft^3/s or 1.99 Mgal/d [table 5]) was 11 percent lower than it was during Period A (3.47 ft^3/s or 2.24 Mgal/d [table 3]). Despite possible small inaccuracies, this analysis indicates that withdrawal from Haiku Tunnel had a measurable effect on both He‘eia and ‘Ioleka‘a Streams, and that the initial effect on He‘eia Stream was about two times greater that it was on ‘Ioleka‘a Stream. As a percentage of their respective Period A_{con} base flows, the effect was greater on ‘Ioleka‘a Stream (64 percent) than on He‘eia Stream (58 percent).

Numerical Groundwater-Model Simulations

The historical-data analysis of this study and results of previous studies indicate that groundwater withdrawals have caused reductions in stream base flow. As part of this study, estimates of how much streamflow might increase if selected groundwater withdrawals are shut down was assessed using simulations on an existing steady-state numerical groundwater model of O‘ahu.

Table 5. Comparison of the effects of Haiku Tunnel withdrawal on He‘eia and ‘Ioleka‘a Streams, O‘ahu, Hawai‘i.

[Negative values indicate decrease from earlier period to later period. Mgal/d, million gallons per day; ft^3/s, cubic feet per second; in/d, inches per day]

Gage number and stream	Average base flow, Period A_{con} (March 6, 1940–October 15, 1940)		Average base flow, Period B (January 1, 1947–September 30, 1970[1])		Change in average base flow between Periods A_{con} and B	
	ft^3/s	Mgal/d	ft^3/s	Mgal/d	ft^3/s	Mgal/d
16275000 He‘eia	3.08	1.99	1.30	0.84	−1.78	−1.15
16278000 ‘Ioleka‘a	1.35	0.87	0.48	0.31	−0.87	−0.56

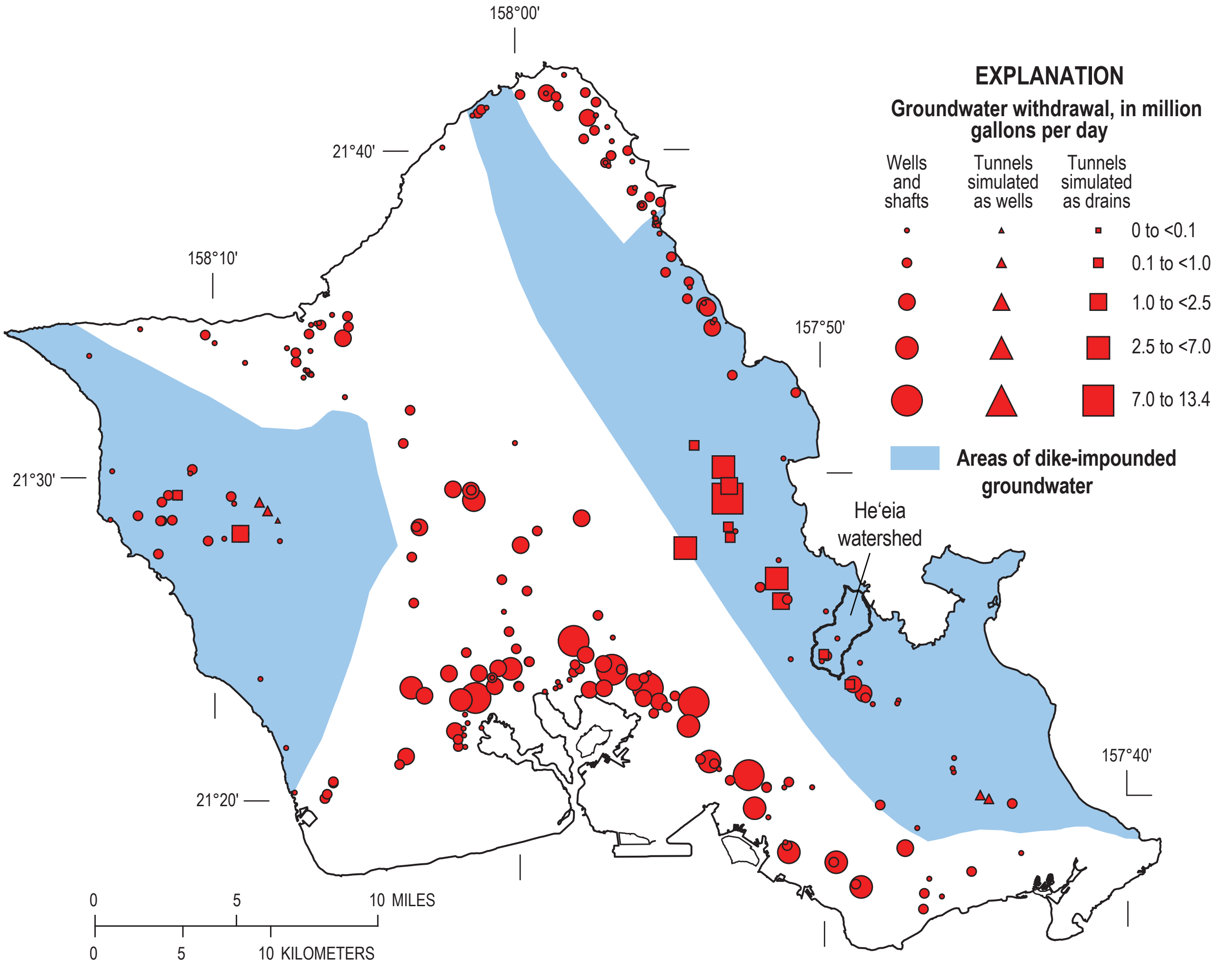
[1] Data from 16278000 on ‘Ioleka‘a Stream ends on February 28, 1970.

Model Description

The steady-state model of Oʻahu was originally created by Izuka and others (2021) to assess the consequences of groundwater development on an island-wide scale. The model was created using MODFLOW-2005 (Harbaugh, 2005) with the Seawater Intrusion Package (SWI2) (Bakker and others, 2013) and was calibrated to average conditions in the period 2001–2010. The model has a single layer that is divided (discretized) into square cells that have horizontal dimensions of 500 ft by 500 ft. The active domain of the model represents only the volcanic aquifers of Oʻahu; sediments in the coastal plain (identified as “caprock” by Izuka and others, 2021) are not simulated as aquifer units, but their effects are simulated using head-dependent discharge boundaries. Streams were also simulated using head-dependent discharge boundaries.

One of the model’s limitations with respect to the objectives of this study is that dikes are not simulated as individual hydrogeologic units. Instead, model zones representing dike-intruded areas were assigned bulk hydraulic properties representing a combination of low-permeability dikes and higher permeability lava flows (the values of the properties were adjusted during model calibration). Anisotropic hydraulic properties in the model are used to simulate preferential flow in the direction of dike alignment in the Koʻolau Range. Another limitation of the model is that not all streams are represented. The locations and traces of the streams simulated in the model are based on the National Hydrography Dataset (U.S. Geological Survey, 2012), but stream reaches on coastal sediments (caprock) and some minor stream reaches on the volcanic aquifer were not simulated. Effects of withdrawals on these reaches are accounted for in the effects on simulated stream reaches and the ocean.

Wells were pumped at their average rates for 2001–2010 (fig. 12). Tunnels were simulated using head-dependent boundaries and were allowed to flow without pumping (as they do in reality). The hydraulic properties of the model cells representing the tunnels were adjusted until the simulated tunnel flow matched the tunnels’ average withdrawal rates for



Coastline modified from U.S. Geological Survey National Hydrography Dataset

Figure 12. Map showing the distribution of simulated groundwater withdrawals (average for 2001–2010) in the numerical groundwater model of Oʻahu, Hawaiʻi. Modified from Izuka and others (2021).

2001–2010. Groundwater withdrawal simulated in the original model by Izuka and others (2021) included 0.60 Mgal/d (0.93 ft^3/s) from Haiku Tunnel, 0.35 Mgal/d (0.54 ft^3/s) from Haiku well, and 0.03 Mgal/d (0.05 ft^3/s) from Iolekaa well.

Simulated Withdrawal Scenarios

Three scenarios were simulated in this study: (1) shutdown of the 0.35 Mgal/d withdrawal from Haiku well, (2) shutdown of the 0.60 Mgal/d withdrawal from Haiku Tunnel, and (3) the combined shutdown of Haiku Tunnel and Haiku well (the effect of shutting down the small withdrawal from Iolekaa well was not addressed in this report because changes to base flows are smaller than the model's accuracy limit). Results of these simulations were compared to the original model to evaluate how the shutdowns affected stream base flows.

Because the O‘ahu model is steady state, this approach assesses the changes that would ultimately result if the tunnel and (or) well were shut down indefinitely and other conditions (such as recharge and withdrawals from other wells and tunnels) remained unchanged. The resulting total increase in groundwater discharge to streams, springs, and the ocean will be equal to the magnitude of the shutdown of Haiku Tunnel and Haiku well.

Simulation Results

In all three scenarios, the simulations indicate that shutting down withdrawals from Haiku Tunnel and Haiku well would increase base flows not only in streams within the He‘eia watershed, but also in streams northwest and southwest along the trend of the Ko‘olau Range (figs. 13, 14, and 15). The distribution of base-flow increases is consistent with preferential groundwater flow parallel to dike orientation in the dike-impounded groundwater of the Ko‘olau Range. The increase in base flow in streams to the northwest is also consistent with previous studies that indicated that base flows in streams as far northwest as Kahalu‘u Stream have been reduced by withdrawal

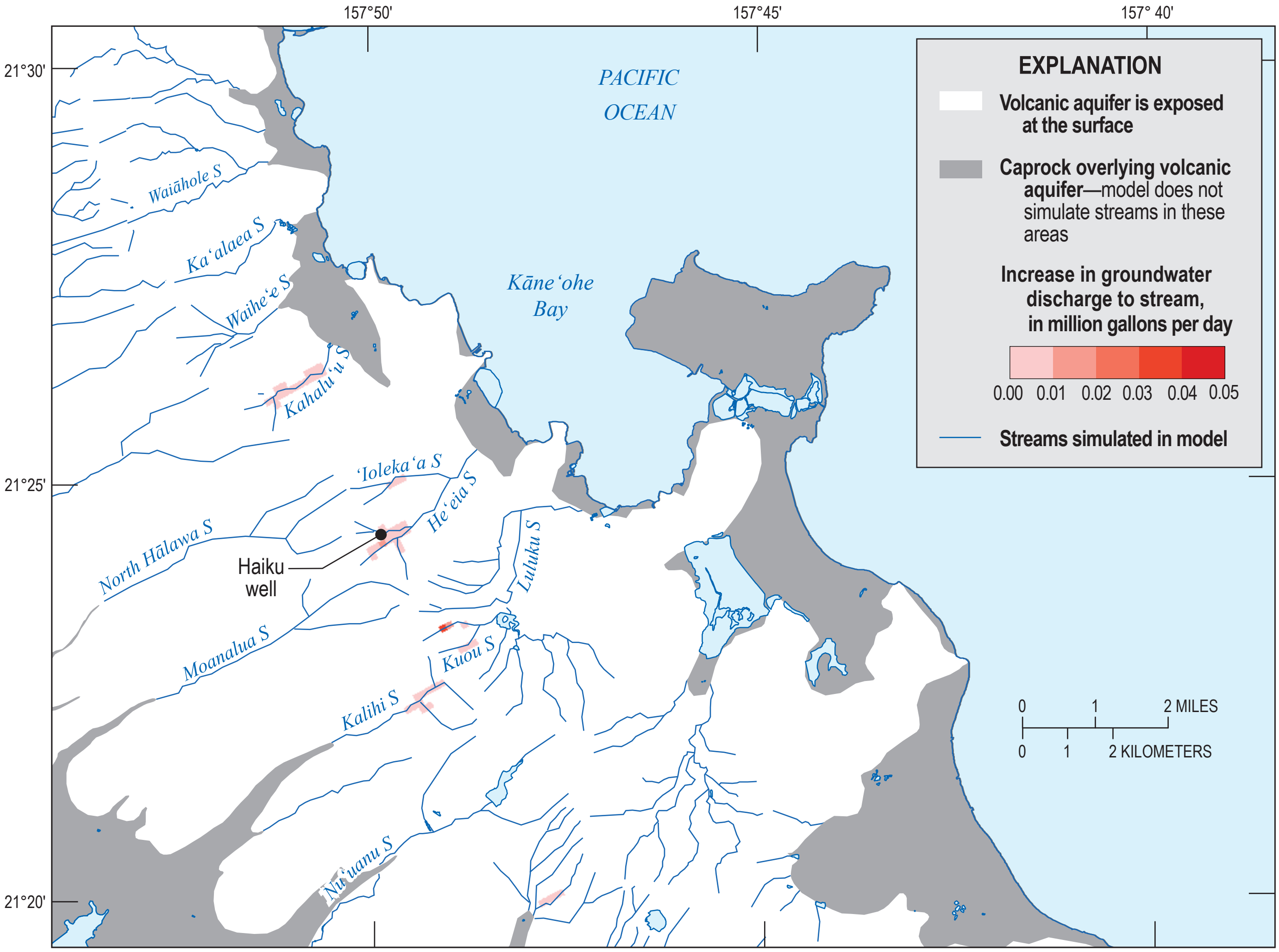


Figure 13. Map showing model-simulated increases in base flow resulting from the shutdown of a withdrawal of 0.35 million gallons per day from Haiku well in the He‘eia watershed, O‘ahu, Hawai‘i.

from Haiku Tunnel (Hirashima 1962, 1963); shutting down tunnel withdrawal will restore some of that base flow. The simulations also show that the shutdown of a larger withdrawal rate will result in farther spread of base-flow increases—when both the tunnel and well are shut down, the base flows increase as far northwest as Kaʻalaea Stream (fig. 15).

The simulated increases in base flows to streams within the Heʻeia watershed are summarized in table 6. Because the Oʻahu model is steady state, expressing the base-flow increases in Heʻeia-watershed streams as a percentage of the change in withdrawal can be informative. The simulations indicate that the shutdown of withdrawal from Haiku well would cause base flow in streams within the Heʻeia watershed to increase by 0.09 Mgal/d (0.14 ft^3/s), shutdown of withdrawal from Haiku Tunnel would cause base flow in streams within the watershed to increase by 0.12 Mgal/d (0.19 ft^3/s), and shutdown of the combined withdrawal from Haiku Tunnel and Haiku well would cause base flow in streams within the watershed to increase by 0.22 Mgal/d (0.34 ft^3/s) (table 6). The base-flow increases constitute about 20 to 26 percent of the withdrawal rate that was shut down in the simulations; the remaining 74 to 80 percent emerges as increased base flow in streams outside the watershed or as groundwater discharge to the wetland and the ocean. The percentages depend on withdrawal rates, the proximity of the tunnel and well to streams and other discharge boundaries, and the distribution of hydraulic properties of the rocks, all of which are subject to the limitations of model discretization discussed below in the "Limitations" section.

In the simulation where only Haiku well was shut down, discharge from Haiku Tunnel increased by 0.04 Mgal/d (0.06 ft^3/s) (table 6). The simulated increase is the model's response to the increase in groundwater head (which caused an increase in the difference in head of across the tunnel's head-dependent discharge boundary) resulting from the shutdown of the well. In reality, changes in flow rate from Haiku Tunnel would be controlled by the tunnel operator. If the tunnel withdrawal is not deliberately increased, the 0.04 Mgal/d (0.06 ft^3/s) would be distributed to other sites of groundwater discharge.

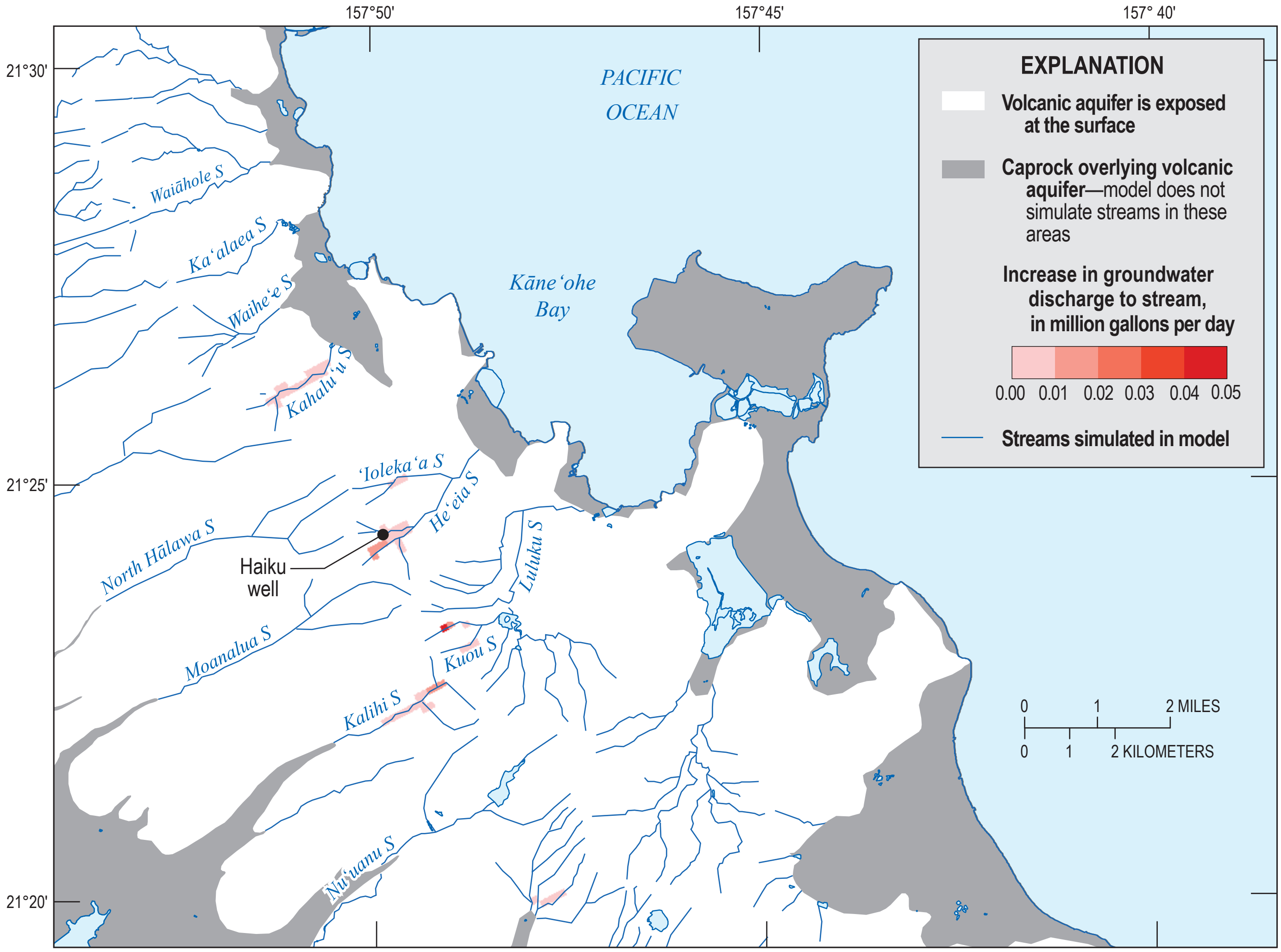


Figure 14. Map showing model-simulated increases in base flow resulting from the shutdown of a withdrawal of 0.60 million gallons per day from Haiku Tunnel in the Heʻeia watershed, Oʻahu, Hawaiʻi.

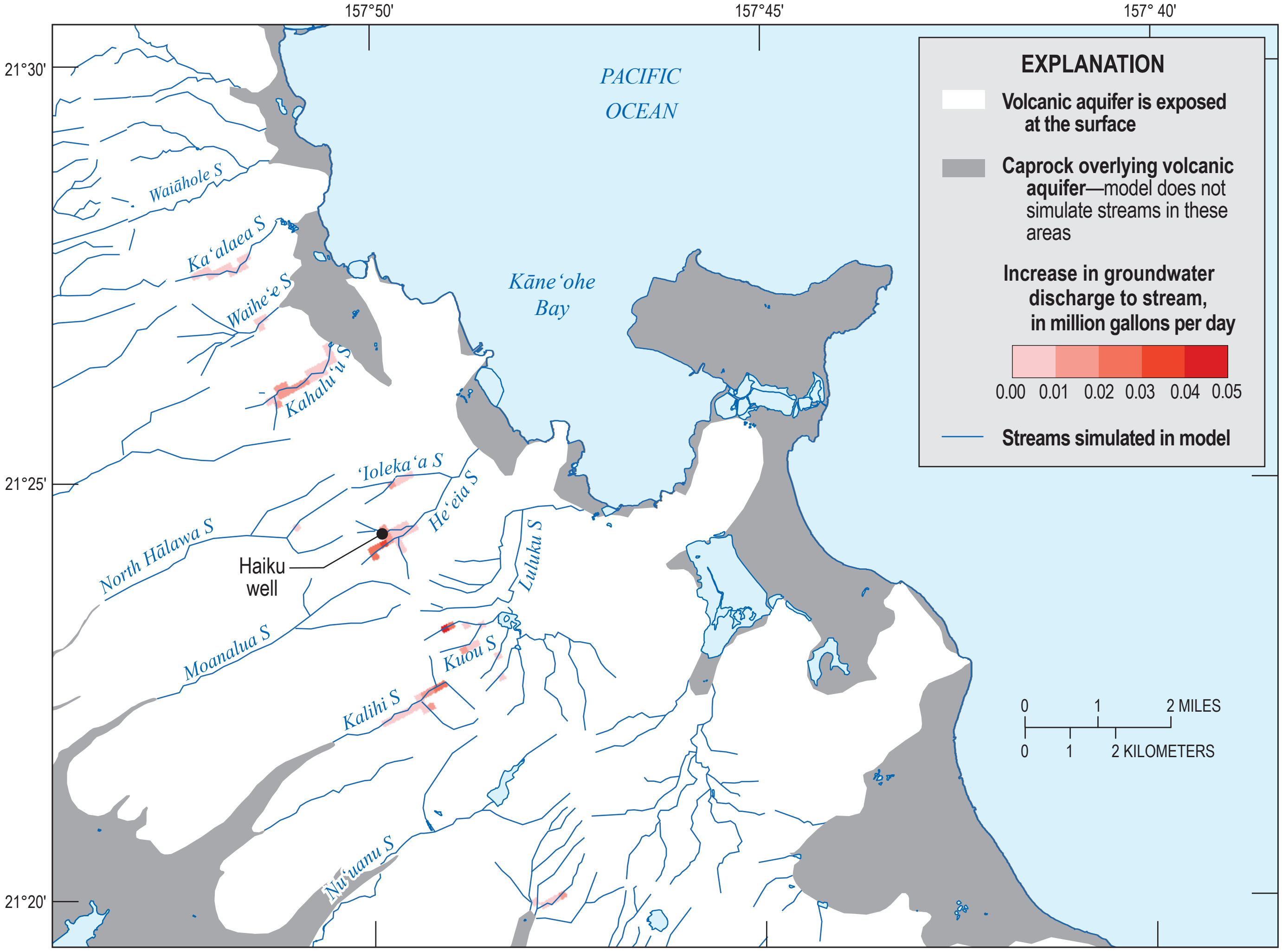


Figure 15. Map showing model-simulated increases in base flow resulting from the shutdown of withdrawals of 0.60 million gallons per day from Haiku Tunnel and 0.35 million gallons per day from Haiku well in the He‘eia watershed, O‘ahu, Hawai‘i.

Table 6. Model-simulated increases in the base flows of streams in the He‘eia watershed, O‘ahu, Hawai‘i, resulting from shutdown of groundwater withdrawals from Haiku Tunnel and Haiku well.

[Mgal/d, million gallons per day]

Simulation	Withdrawal reduction (Mgal/d)			Base-flow increase			
	Haiku Tunnel	Haiku well	Total	He‘eia Stream (Mgal/d)	‘Ioleka‘a Stream (Mgal/d)	Total (Mgal/d)	Percent of withdrawal reduction
Shutdown of Haiku well	−0.04[*]	0.35	0.35	0.08	0.01	0.09	26
Shutdown of Haiku Tunnel	0.60	0.00	0.60	0.11	0.02	0.12	20
Shutdown of Haiku Tunnel and Haiku well	0.60	0.35	0.95	0.19	0.03	0.22	23

[*] In this simulation, the withdrawal increase (-0.04 Mgal/d) from Haiku Tunnel is the model’s response to the increase in groundwater head caused by the shutdown of Haiku well, not a deliberate increase in simulated tunnel withdrawal.

Implications for the Effects of Groundwater Withdrawal on Stream Flow

Both methods of analyzing historical streamflow data (flow-duration and base-flow-separation analyses) indicate a large change in stream base flow resulting from the initial withdrawal from Haiku Tunnel—base-flow reduction accounts for 75 to 79 percent of the tunnel's initial withdrawal. Both analyses also indicate that when tunnel draft was reduced in Periods IIIa and C, the base-flow increase constitutes a much smaller percentage (15 to 29 percent) of the change in withdrawal. Although some of these base-flow changes may be linked to rainfall variations, the small-percentage base-flow increases following withdrawal reductions are consistent with the similar small-percentage base-flow responses that resulted in the model simulations (which are free of rainfall variations) of the shutdowns of Haiku Tunnel and Haiku well. Model-simulated base-flow increases within the Heʻeia watershed accounted for only 20 to 26 percent of the shutdown of withdrawals.

The analyses of historical data and the model simulations indicate that decreases in withdrawals do not restore base flow to the same degree that initiation of withdrawal had decreased base flow. The historical-data analyses' estimate of the tunnel's initial impact is computed relative to a nearly pristine condition. Haiku Tunnel was one of the earliest to develop dike-impounded groundwater in the Koʻolau Range (water-development tunnels that predate Haiku Tunnel are more than 5 miles from the study area). In contrast, the model simulated the shutdown of Haiku Tunnel during a period (2001–2010) when other large-producing water tunnels and wells outside but near the Heʻeia watershed were in operation (fig. 12). The model simulations demonstrate that, climate changes notwithstanding, shutting down withdrawal from Haiku Tunnel today will not restore base flow to predevelopment rates if withdrawals from all other wells and tunnels continue.

Study Limitations

The analyses of historical data and the numerical-model simulations in this study were designed to improve understanding of the hydrology of the Heʻeia watershed, especially the connection between groundwater withdrawals and stream base flow. Although findings of this study have implications for how changes in withdrawal may affect stream base flow in the future, the study did not address some key factors—such as changes in climate and land use—that can substantially affect the future interaction between groundwater and streamflow and, in turn, the availability of water in the watershed.

This study included an analysis of rainfall to assess the possibility that observed changes in base flow in the Heʻeia watershed could be related to climate variations rather than groundwater withdrawals, but did not assess changes in relation to long-term trends, such as the downward trend in base flow in 1913–2008 described by Oki (2004) and Bassiouni and Oki (2013). Their analyses did not include the gages in the Heʻeia watershed, and the declining trends they identified are much smaller than the changes related to groundwater withdrawal described in this study. Their observed trends also are apparent on multiple islands in Hawaiʻi, which suggests they are related, at least in part, to regional factors such as climate change. Even so, because groundwater withdrawals in the Heʻeia watershed can affect streams beyond the watershed boundaries, they may have contributed to the observed long-term decreases on the Koʻolau Range. Bassiouni and Oki (2013) attributed much of the downward trend they observed in the 1913–2008 period to a substantial downward shift around 1943, which is close to the initiation of withdrawal from Haiku Tunnel. The effects of groundwater withdrawals from the Heʻeia watershed and elsewhere in the Koʻolau Range would be superimposed on the broader regional trends.

The flow-duration and base-flow-separation analyses are limited by the availability of historical streamgage data. Although this study had the benefit of a long-term dataset from the active gage 16275000 on Heʻeia Stream that has been in operation since 1914, the data had multiyear gaps, one of which spanned from October 1919 through June 1939, substantially reducing the amount of data prior to the onset of withdrawals. Data from gage 16278000 on ʻIolekaʻa Stream did not have large gaps, but the record spans only a period from 1940 to 1970 with less than a year of data prior to the onset of withdrawals. The two gages also monitored only the upper 38 percent of the watershed; previous studies (for example, Izuka and others, 1993) indicated that groundwater continues to discharge below these gages, so the base flows from the historical data available for this study represent only a fraction of the groundwater discharge to streams in the Heʻeia watershed.

The ability to separate historical base-flow variations caused by rainfall variations from those caused by withdrawals was limited by the availability of long-term rain-gage data. Because the nearest rain gage (Kalihi Res Site 777.0) with a dataset that spanned the entire period of interest in this study was 1.3 mi outside of the nearest boundary of the Heʻeia watershed, analyses in this study were limited to multi-year averages to avoid spatial variations in short-term rainfall. Although the conditions at the rain gage may not match those in the He'eia watershed precisely, the gage was in a region of orographic rainfall similar to that of the study area.

The precision of the model simulations in this study is limited because the preexisting model that was used has discretization and simplifications intended for island-scale assessments. The model cannot simulate streamflow effects at a greater spatial precision than the 500-ft dimensions of the model cells, cannot simulate withdrawals from different dike compartments, and cannot distinguish impacts on waterbodies on the caprock (such as streams and wetlands) from impacts on groundwater discharge to the ocean. Simulation of these aspects requires a model with finer discretization and fewer simplifications than the model used in this study, and more detailed data on the specific hydrogeology of the Heʻeia watershed and surrounding areas would be needed. Also, because the model is steady state, it cannot assess the rate at which changes to streams would occur relative to changes in withdrawals that cause them; modifying the model so that it can simulate time-dependent changes requires data on aquifer storage properties and variations in recharge, withdrawal, groundwater levels, streamflow, and other conditions with time.

Summary and Conclusions

Analysis of historical streamflow data from gages 16275000 on Heʻeia Stream and 16278000 on ʻIolekaʻa Stream shows variations in base flow that correspond to the onset of, and subsequent variations in, withdrawal from Haiku Tunnel. During tunnel construction (1940–1941), groundwater flowing freely from the penetrated dike compartments was released into Heʻeia Stream, causing an artificial rise in base flow at gage 16275000. After tunnel construction, base flow at both gages showed a declining trend. As tunnel withdrawal continued in subsequent decades, base flow fluctuated inversely with withdrawal, but the average base flow was lower than it was prior to tunnel construction.

Analyses of streamflow data at gage 16275000 indicate a decrease in average base flow of 1.37 to 1.40 Mgal/d (2.11 to 2.17 ft^3/s) that corresponds with average groundwater withdrawals of 1.73 to 1.87 Mgal/d (2.68 to 2.89 ft^3/s) from Haiku Tunnel during the first few decades (starting from 1941) of its operation. Whereas changes in rainfall during this period are not sufficient to account for the changes in base flow, it is likely that most of the apparent base-flow decrease reflects the impact of tunnel withdrawals on the stream. Comparison of data from gages 16275000 on Heʻeia Stream and 16278000 on ʻIolekaʻa Stream indicates that the effect of the tunnel on average base flow was about two times greater in Heʻeia Stream than in ʻIolekaʻa Stream, but relative to their respective predevelopment base flows, the effect was greater on ʻIolekaʻa Stream than on Heʻeia Stream.

In the 1980s, withdrawal from Haiku Tunnel had decreased and withdrawal from Haiku well started. Base flow at gage 16275000 appears to have been affected less by withdrawal from Haiku well than it was by withdrawal from Haiku Tunnel, which is consistent with the conceptualization that the well taps a different dike compartment than the tunnel. Analyses of streamflow data indicate that average base flow increased 0.15 to 0.21 Mgal/d (0.23 to 0.32 ft^3/s) at gage 16275000 when average withdrawal from Haiku Tunnel decreased by 0.7 to 1.00 Mgal/d (1.11 to 1.55 ft^3/s). Increase in rainfall may account for some of the base-flow increase.

Simulations using a numerical groundwater model indicate that shutting down withdrawals from Haiku Tunnel and Haiku well would increase base flows not only in streams within the Heʻeia watershed, but also in other watersheds of the Koʻolau Range. The larger the withdrawal rate that is shut down, the farther the spread of base-flow increases will be. Simulated shutdown of the 0.35 Mgal/d withdrawal from Haiku well caused base flow of streams within the Heʻeia watershed to increase by 0.09 Mgal/d or 26 percent of the withdrawal reduction (the other 74 percent emerges as increased groundwater discharge to streams outside the watershed or to the wetland and the ocean). Simulated shutdown of the 0.60 Mgal/d withdrawal from Haiku Tunnel caused the base flow of streams within the watershed to increase by 0.12 Mgal/d or 20 percent of withdrawal reduction. Simulated shutdown of the combined 0.95 Mgal/d withdrawal from Haiku Tunnel and Haiku well caused base flow of streams within the watershed to increase by 0.22 Mgal/d or 23 percent of the withdrawal reduction.

The model simulation and analyses of streamflow data demonstrate that, climate changes notwithstanding, shutting down withdrawal from Haiku Tunnel has not in the past, and will not in the future, restore base flow to predevelopment rates. The analyses of streamflow data indicate that the decrease in base flow at gage 16275000 in the first few decades of Haiku Tunnel operation withdrawal was 75 to 79 percent of the tunnel's average withdrawal. In contrast, the increase in base flow when tunnel withdrawal was reduced in the 1980s was only 15 to 29 percent of the withdrawal reduction (the percentage may be even smaller because some of the base flow increase may have resulted from increased rainfall). The model simulations also indicate that if Haiku Tunnel and (or) Haiku well were shut down, only about 20 to 26 percent of the withdrawal decrease would return as base flow to streams within the Heʻeia watershed. The tunnel's initial impact, as indicated by the analysis of historical data, is relative to a nearly pristine condition that existed prior to 1940. This condition no longer exists because other large-producing tunnels and wells near the Heʻeia watershed have since begun withdrawing water from the same dike-impounded aquifer. Reduction or shutdown of withdrawals from the wells and tunnel in the Heʻeia watershed cannot restore streamflow to predevelopment rates if withdrawals from all other wells and tunnels continue.

References Cited

Bakker, M., Schaars, F., Hughes, J.D., Langevin, C.D., and Dausman, A.M., 2013, Documentation of the seawater intrusion (SWI2) package for MODFLOW: U.S. Geological Survey Techniques and Methods, book 6, chap. A46, 47 p., https://pubs.usgs.gov/tm/6a46/.

Barlow, P.M., Cunningham, W.L., Zhai, T., and Gray, M., 2015, U.S. Geological Survey Groundwater Toolbox, a graphical and mapping interface for analysis of hydrologic data (version 1.0)—User guide for estimation of base flow, runoff, and groundwater recharge from streamflow data: U.S. Geological Survey Techniques and Methods, book 3, chap. B10, 27 p., https://dx.doi.org/10.3133/tm3B10.

Bassiouni, M., and Oki, D.S., 2013, Trends and shifts in streamflow in Hawai‘i, 1913–2008: Hydrological Processes, v. 27, no. 10, p. 1484–1500, http://onlinelibrary.wiley.com/doi/10.1002/hyp.9298/full.

Cheng, C.L., 2016, Low-flow characteristics for streams on the Islands of Kaua‘i, O‘ahu, Moloka‘i, Maui, and Hawai‘i, State of Hawai‘i: U.S. Geological Survey Scientific Investigations Report 2016-5103, 36 p., https://doi.org/10.3133/sir20165103.

Chu, P.-S., and Chen, H., 2005, Interannual and interdecadal rainfall variations in the Hawaiian islands: Journal of Climate, v. 18, p. 4,796–4,813.

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

Giambelluca, T.W., Chen, Q., Frazier, A.G., Price, J.P., Chen, Y.-L., Chu, P.-S., Eischeid, J.K., and Delparte, D.M., 2013: Online Rainfall Atlas of Hawai‘i: Bulletin of the American Meteorological Society 94, p. 313–316, https://doi: 10.1175/BAMS-D-11-00228.1.

Giambelluca, T.W., and Schroeder, T.A., 1998, Climate, *in* Juvik, S.P., and Juvik, J.O., eds., Atlas of Hawai‘i (3d ed.): Honolulu, University of Hawai‘i Press, 333 p.

Harbaugh, A.W., 2005, MODFLOW-2005, The U.S. Geological Survey modular ground-water model—the ground-water flow process: U.S. Geological Survey Techniques and Methods 6-A16, variously p. https://doi.org/10.3133/tm6A16.

Hirashima, G.T., 1962, Effect of the Haiku Tunnel on Kahaluu Stream, Oahu, Hawaii: U.S. Geological Survey Professional Paper 450C, p. 118–120.

Hirashima, G.T., 1963 Influence of Water-Development Tunnels on Streamflow-Groundwater Relations in Haiku-Kahaluu Area Oahu, Hawaii: State of Hawaii Department of Land and Natural Resources Division of Water and Land Development Circular C21, 11 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.

Izuka, S.K., Hill, B.R., Shade, P.J., and Tribble, G.W., 1993, Geohydrology and possible transport routes of polychlorinated biphenyls in Haiku Valley, Oahu, Hawaii: U.S. Geological Survey Water-Resources Investigations Report 92–4168, 48 p.

Izuka, S.K., Engott, J.A., Rotzoll, K., Bassiouni, M., Johnson, A.G., Miller, L.D., and Mair, A., 2018, Volcanic aquifers of Hawai‘i—Hydrogeology, water budgets, and conceptual models (ver. 2.0, March 2018): U.S. Geological Survey Scientific Investigations Report 2015–5164, 158 p., https://doi.org/10.3133/sir20155164.

Izuka, S.K., Rotzoll, K., and Nishikawa, T., 2021, Volcanic aquifers of Hawai‘i—Construction and calibration of numerical models for assessing groundwater availability on Kaua‘i, O‘ahu, and Maui: U.S. Geological Survey Scientific Investigations Report 2020–5126, 63 p., https://doi.org/10.3133/sir20205126.

Izuka, S.K., and Rotzoll, K., 2023, Volcanic aquifers of Hawai‘i—Contributions to assessing groundwater availability on Kaua‘i, O‘ahu, and Maui: U.S. Geological Survey Professional Paper 1876, 100 p., https://doi.org/10.3133/pp1876

Lau, L.S., and Mink, J.F., 2006, Hydrology of the Hawaiian Islands: Honolulu, University of Hawai‘i Press, 274 p.

Macdonald, G.A., Davis, D.A., and Cox, D.C., 1960, Geology and groundwater resources of the island of Kauai, Hawaii: Hawaii Division of Hydrography Bulletin 13, 212 p.

National Centers for Environmental Information, 2022, Global Historical Climatology Network–Daily (GHCN-Daily), Version 3: accessed on May 5, 2022 at https://www.ncei.noaa.gov/access/search/data-search/daily-summaries.

Oki, D.S., 2004, Trends in streamflow characteristics at long-term gaging stations, Hawaii: U.S. Geological Survey Scientific Investigations Report 2004–5080, 116 p.

Rotzoll, K., 2024, MODFLOW-2005 and SWI2 models for assessing groundwater and surface-water interactions in the Heeia Watershed, Oahu, Hawaii: U.S. Geological Survey data release, https://doi.org/10.5066/P91JM5FZ.

Rotzoll, K., and El-Kadi, A.I., 2008, Estimating hydraulic conductivity from specific capacity for Hawaii aquifers, USA: Hydrogeology Journal, v. 16, p. 969–979. https://doi.org/10.1007/s10040-007-0271-0

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

Sherrod, D.R., Sinton, J.M., Watkins, S.E., and Brunt, K.M., 2021, Geologic map of the State of Hawai‘i: U.S. Geological Survey Scientific Investigations Map 3143, 72 p., 5 sheets, scales 1:100,000 and 1:250,000, https://doi.org/10.3133/sim3143.

Sinton, J.M., Eason, D.E., Tardona, M., Pyle, D., van der Zander, I., Guillou, H., Clague, D.A., and Mahoney, J.J., 2014, Ka‘ena Volcano—A precursor volcano of the island of O’ahu, Hawai’i: Geological Society of America Bulletin, v. 126, no. 9/10, p. 1219–1244, https://doi.org/10.1130/B30936.1

Soroos, R.L., 1973, Determination of hydraulic conductivity of some Oahu aquifers with step-drawdown test data: Honolulu, University of Hawaii, M.S. thesis, 239 p.

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, 479 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.

U.S. Geological Survey, 2012, The National Map national hydrography dataset: U.S. Geological Survey web page, accessed February 12, 2013, at http://nhd.usgs.gov/data.

U.S. Geological Survey, 2022, U.S. Geological Survey National Water Information System (NWIS), http://dx.doi.org/10.5066/F7P55KJN, accessed between January 24, 2021 and July 11, 2022 at https://waterdata.usgs.gov/nwis.

VTN Pacific, 1983, Revised environmental impact statement for Iolekaa Well, Kaneohe, Oahu, Hawaii, Tax Map Key: 4-6-27:11: 42 p. plus appendix.

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

Walker, G.P.L., 1987, The dike complex of Koolau volcano, Oahu—Internal structure of a Hawaiian rift zone, chap. 41 *of* Decker, R.W., Wright, T.L, and Stauffer, P.H., eds., Volcanism in Hawaii: U.S. Geological Survey Professional Paper 1350, v. 2, p. 961–993.

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