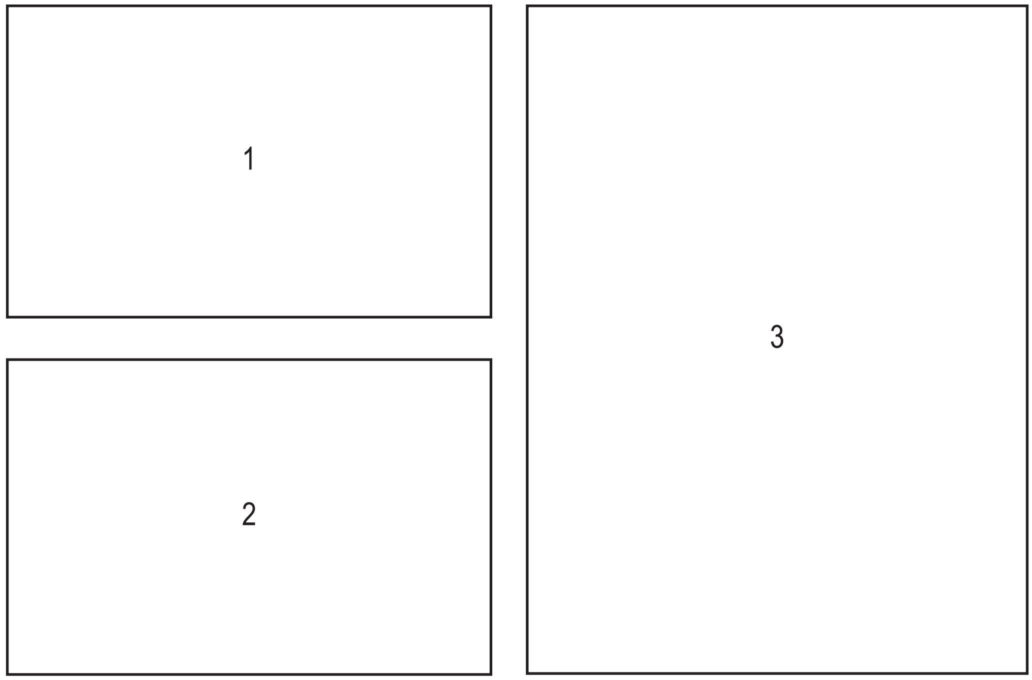
Prepared in cooperation with the State of Hawai‘i Commission on Water Resource Management and in collaboration with the University of Hawai‘i Water Resources Research Center

# Water-Resource Management Monitoring Needs, State of Hawai‘i

Scientific Investigations Report 2020–5115

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




**Cover images:**

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(1) Photograph of Nakula climate station located at altitude of about 5,300 feet on southern Halekalā, island of Maui, Hawai‘i. Photograph by Joseph J. Kennedy, U.S. Geological Survey, 2018.

(2) Photograph of continuous-record streamflow-gaging station (U.S. Geological Survey station 16275000), island of O‘ahu, Hawai‘i. Photograph by Benjamin H. Shimizu, U.S. Geological Survey, 2019.

(3) Photograph of northwest Kilohana monitoring well 2 (U.S. Geological Survey station 220126159261501) in the Līhu‘e basin, island of Kaua‘i, Hawai‘i. Photograph by Todd K. Presley, U.S. Geological Survey, 2012.

# Water-Resource Management Monitoring Needs, State of Hawaiʻi

By Chui Ling Cheng, Scot K. Izuka, Joseph J. Kennedy, Abby G. Frazier, Thomas W. Giambelluca

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

**U.S. Department of the Interior**
DAVID BERNHARDT, Secretary

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James F. Reilly II, Director

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# Executive Summary

A fundamental component of water-resource management and protection is an effective monitoring program that considers the spatial and temporal scale of data-collection needs, range of applicability, current and future water-resource issues, data quality and accessibility, and cost-effectiveness of acquiring the data. In cooperation with the State of Hawai‘i Commission on Water Resource Management (CWRM) and in collaboration with the University of Hawai‘i Water Resources Research Center (WRRC), the U.S. Geological Survey (USGS) developed a water-resource monitoring program—a rainfall, streamflow, and groundwater data-collection program—that meets State needs for water-resource assessment, management, and protection in Hawai‘i. Current and foreseeable issues related to water-resource management and climate-change effects were identified in collaboration with CWRM, WRRC, County water departments, and other stakeholders. These issues were used to develop a set of criteria for evaluating data-collection sites for the monitoring program and a set of goals the program should achieve.

Data-collection sites were divided into two data-collection networks: (1) a resource-management network to determine effects of water- and land-use changes on surface-water and groundwater resources, and (2) a climate-response network to determine effects of climate change on rainfall, surface-water, and groundwater resources in representative hydrogeologic settings. Data-collection sites currently (2018) being operated in Hawai‘i were evaluated using this grouping, and additional data-collection sites to supplement the current monitoring program to address State needs were selected on the basis of their usefulness for characterizing anthropogenic effects to water resources or representing natural conditions. Additional data-collection sites for the data-collection networks were selected, and consideration was given to reactivating discontinued sites with substantial historical data. Data-collection strategies associated with the data-collection sites consist of a combination of continuous long-term monitoring and occasional and periodic intensive monitoring to evaluate trends and climate-change effects and to enhance spatial understanding of hydrologic conditions and address water-resource issues in priority areas—areas that currently have water-availability issues or are expected to have the greatest socioeconomic or ecological effects because of climate change—respectively.

## Rainfall-Monitoring Program

The rainfall-monitoring program, developed in collaboration with WRRC, focuses on increasing rain-gage density and spatial distribution in a manner that will enhance coverage across the Hawaiian Islands by reactivating rain gages that have historical data, are in areas with limited rain-gage coverage, and (or) are located in rainfall priority areas, and by installing new rain gages in priority areas where no prior data exist. Rainfall priority areas consist of urban and agricultural lands, areas with high rainfall and high-rainfall gradient, and areas within the trade-wind inversion band. Although O‘ahu and Maui have island-wide rain-gage densities that meet the World Meteorological Organization (WMO) minimum rain-gage density standard, there is insufficient coverage of rainfall priority areas on these islands. The islands of Kaua‘i, Moloka‘i, Lāna‘i, and Hawai‘i do not have rain-gage densities that meet the WMO minimum-density standard and lack rain-gage coverage in areas, including rainfall priority areas. The rainfall-monitoring program is illustrated in figure ES1 and consists of 381 active rain gages and 173 additional rain gages that are either new or inactive rain gages that supplement the current program. The implementation of all additional rain gages would increase effective rain-gage coverage by over 20 percent of land area and over 25 percent of rainfall priority areas.

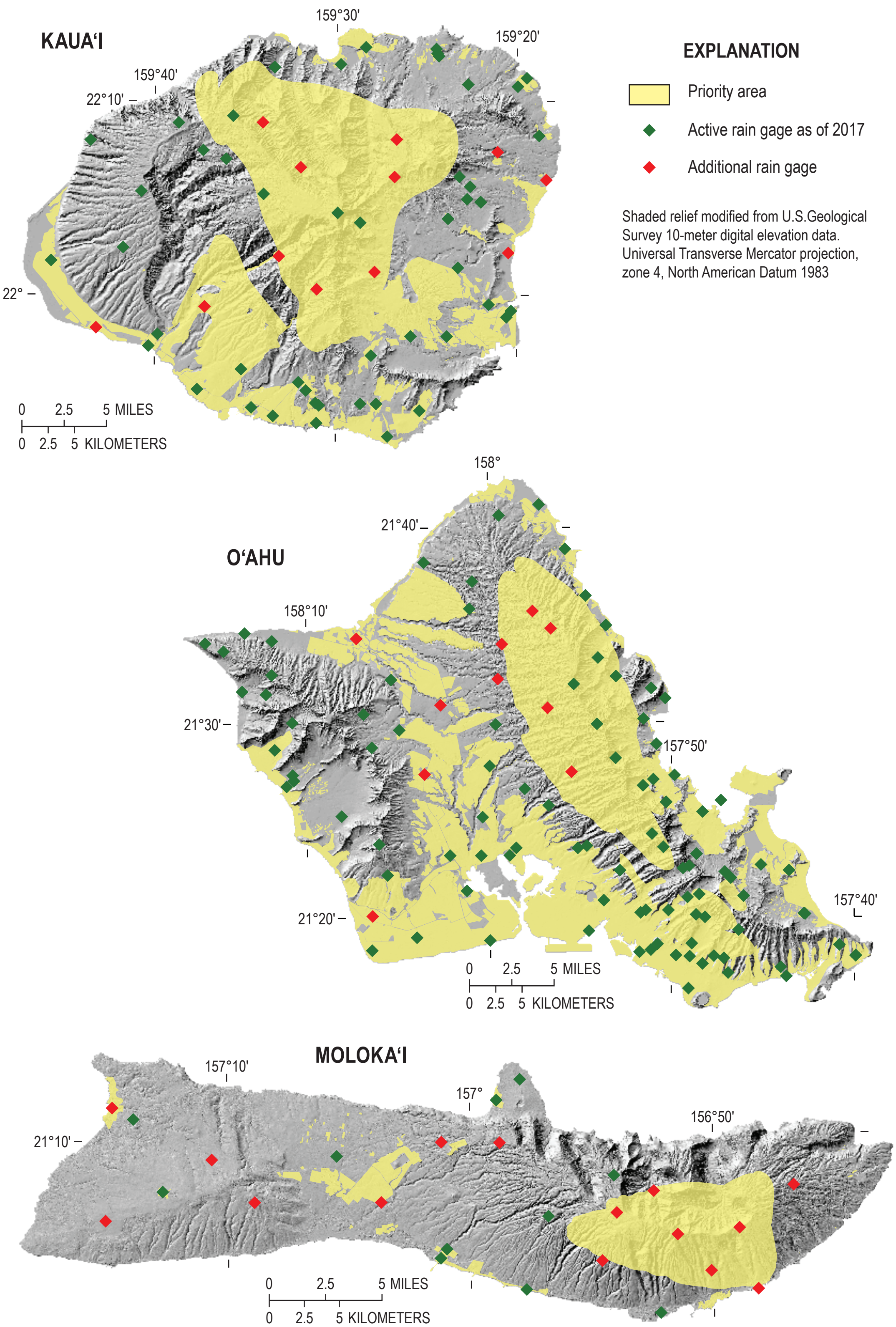


**Figure ES1.** Maps showing the rainfall-monitoring program for the Hawaiian Islands of Kaua‘i, O‘ahu, Moloka‘i, Maui, Lāna‘i, and Hawai‘i.

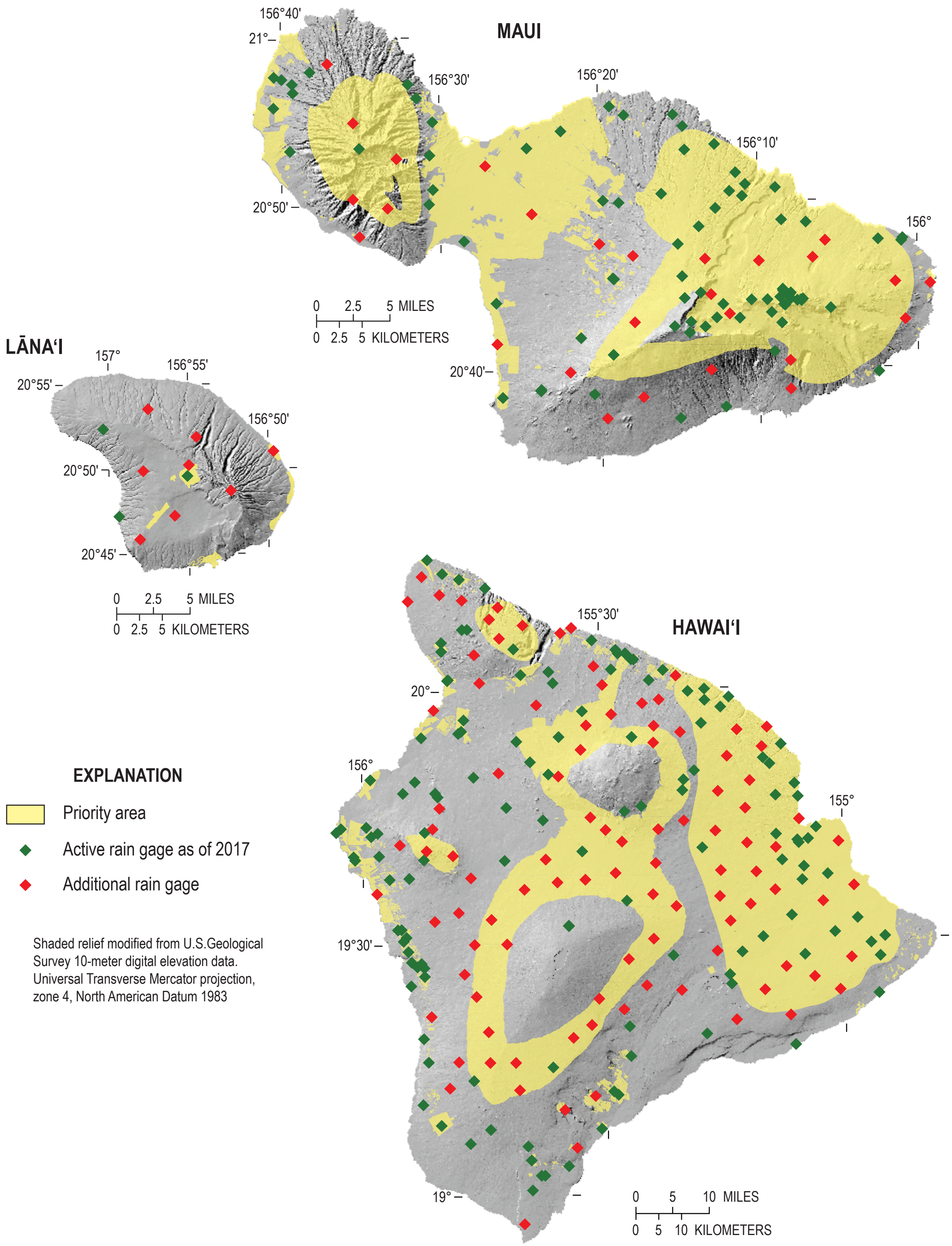


**Figure ES1.** —Continued

## Surface-Water Resource-Monitoring Program

The surface-water resource-monitoring program is illustrated in figure ES2, and it consists of 142 active stations currently operated by the USGS or CWRM and 60 additional stations that are either new streamflow or ditch-flow-gaging stations or inactive surface-water streamflow-gaging stations to be reactivated to supplement the current program. The resource-management network focuses data collection on State-identified surface-water priority areas, which include streams with major surface-water diversions, with established interim instream-flow standards, in surface-water management areas, and that support water leases. Streams in areas with limited or no existing hydrologic data are identified for monitoring to address the lack of hydrologic information for instream-flow standard development. The climate-response network includes active continuous stations with long-term records of natural flow for determining streamflow characteristics and analyzing long-term streamflow trends. Generally, the different hydrogeologic settings on Kaua‘i, O‘ahu, and Maui are represented by the active continuous stations selected for the monitoring program. Additional monitoring is needed for some areas on the islands of Moloka‘i and Hawai‘i. The network also identified 104 streams that need seepage-analysis discharge measurements for determining surface water and groundwater interaction. No surface-water monitoring needs were identified for the island of Lāna‘i, because no water-resource needs were identified by the State.

## Groundwater-Resource Monitoring Program

The groundwater-resource monitoring program consists of 67 active sites (wells) monitored by the USGS, CWRM, and Honolulu Board of Water Supply, for both the resource management and climate response networks (fig. ES3). In this study, 204 additional sites are selected to supplement the active sites in the two networks. The sites include long-term water-level sites for monitoring trends in groundwater levels and specific-conductance profiling sites to monitor movement of the freshwater-saltwater transition zone in the aquifer. Because water-level measurements are made as part of the specific-conductance profiling routine, specific-conductance profiling sites are also considered long-term water-level sites.

Additional sites in the resource-management network include 145 long-term water-level monitoring sites and 44 specific-conductance monitoring sites. These sites were distributed on the basis of priorities that considered withdrawal rates; reduction in groundwater storage; reduction in discharge to streams and the ocean; reduction in flow to adjacent aquifers; potential recharge reduction in the future; and whether an aquifer had limited alternative sources or hydrogeologic uncertainties. Generally, more sites were placed in areas with higher priority. The resource-management network identified 11 synoptic surveys to provide more information on spatial distribution of water levels in the selected regions.

Sixteen additional sites and two active sites in figure ES3 constitute the climate-response network. The network consists of 12 long-term water-level monitoring sites and 4 specific-conductance profiling sites. To isolate the effects of climate, the additional sites for the climate-response network were distributed in areas that had minimal groundwater development. Sites were also chosen to monitor the full range of hydrogeologic and climate settings in Hawai‘i.

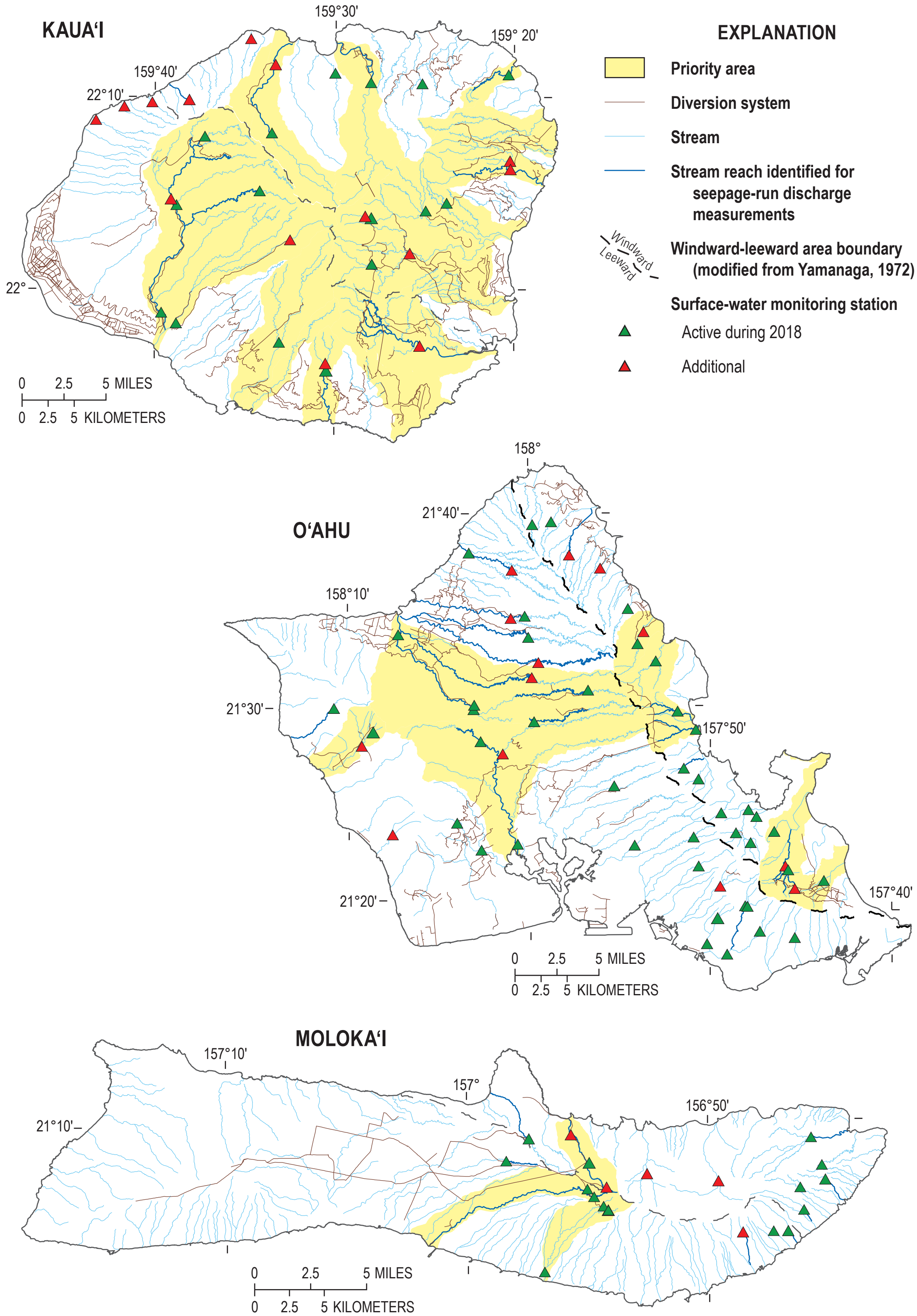


**Figure ES2.** Maps showing the surface-water resource-monitoring program for the Hawaiian Islands of Kaua‘i, O‘ahu, Moloka‘i, Maui, and Hawai‘i. No surface-water monitoring needs were identified for the island of Lāna‘i, because no water-resource needs were identified by the State.

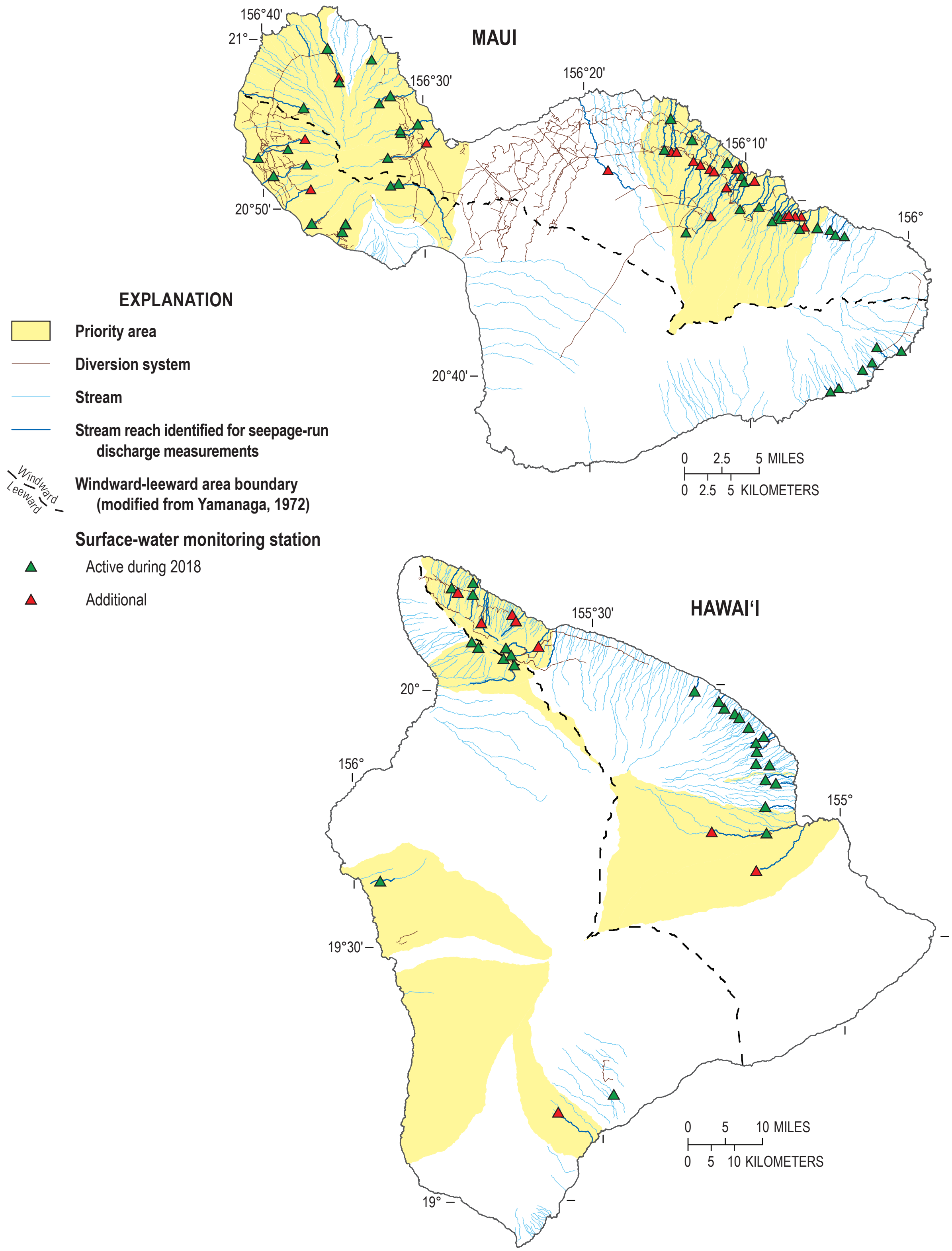


**Figure ES2.** —Continued

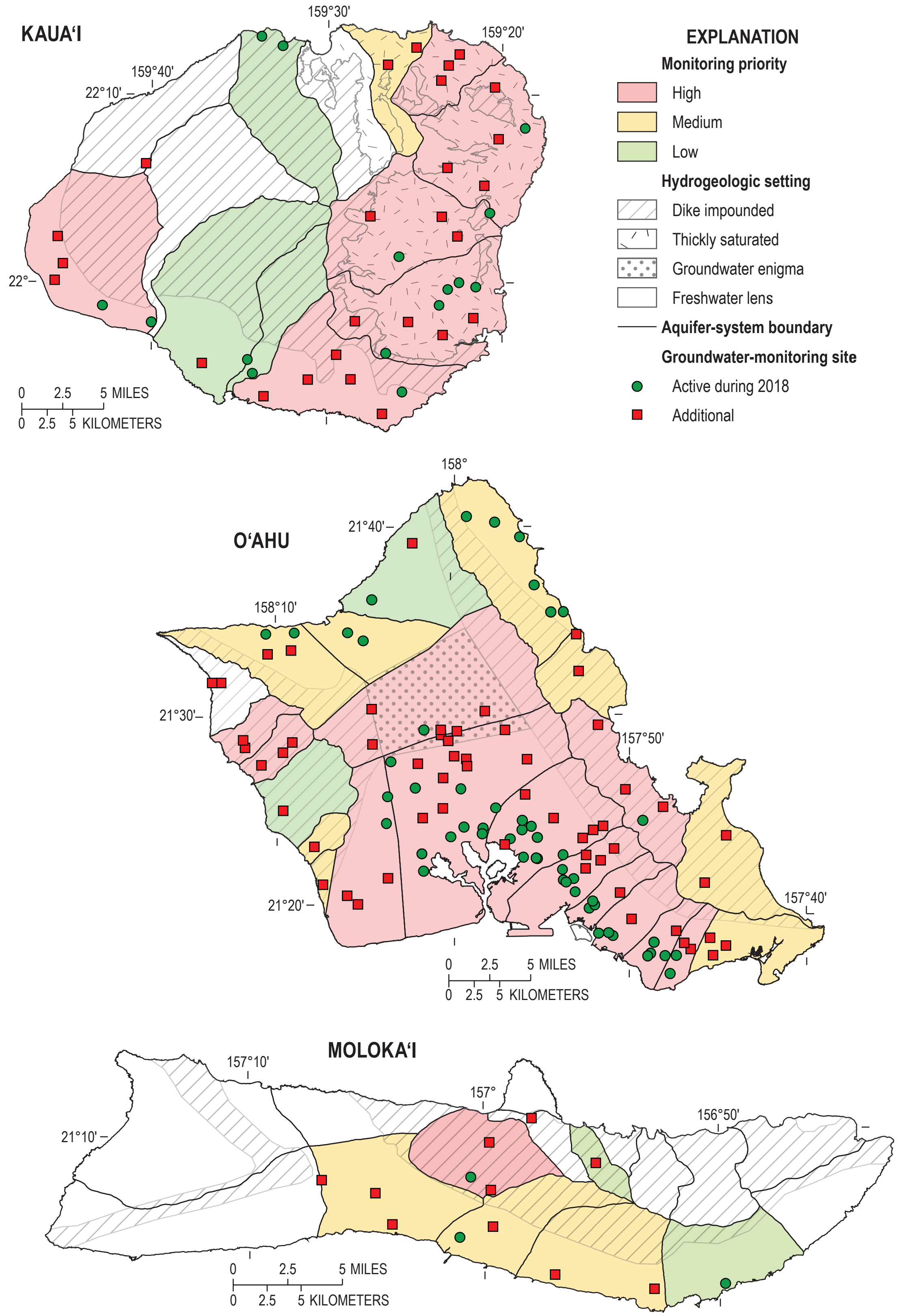


**Figure ES3.** Maps showing the groundwater-resource monitoring program for the Hawaiian Islands of Kaua'i, O'ahu, Moloka'i, Maui, Lāna'i, and Hawai'i. White background indicates aquifer systems that are not prioritized.

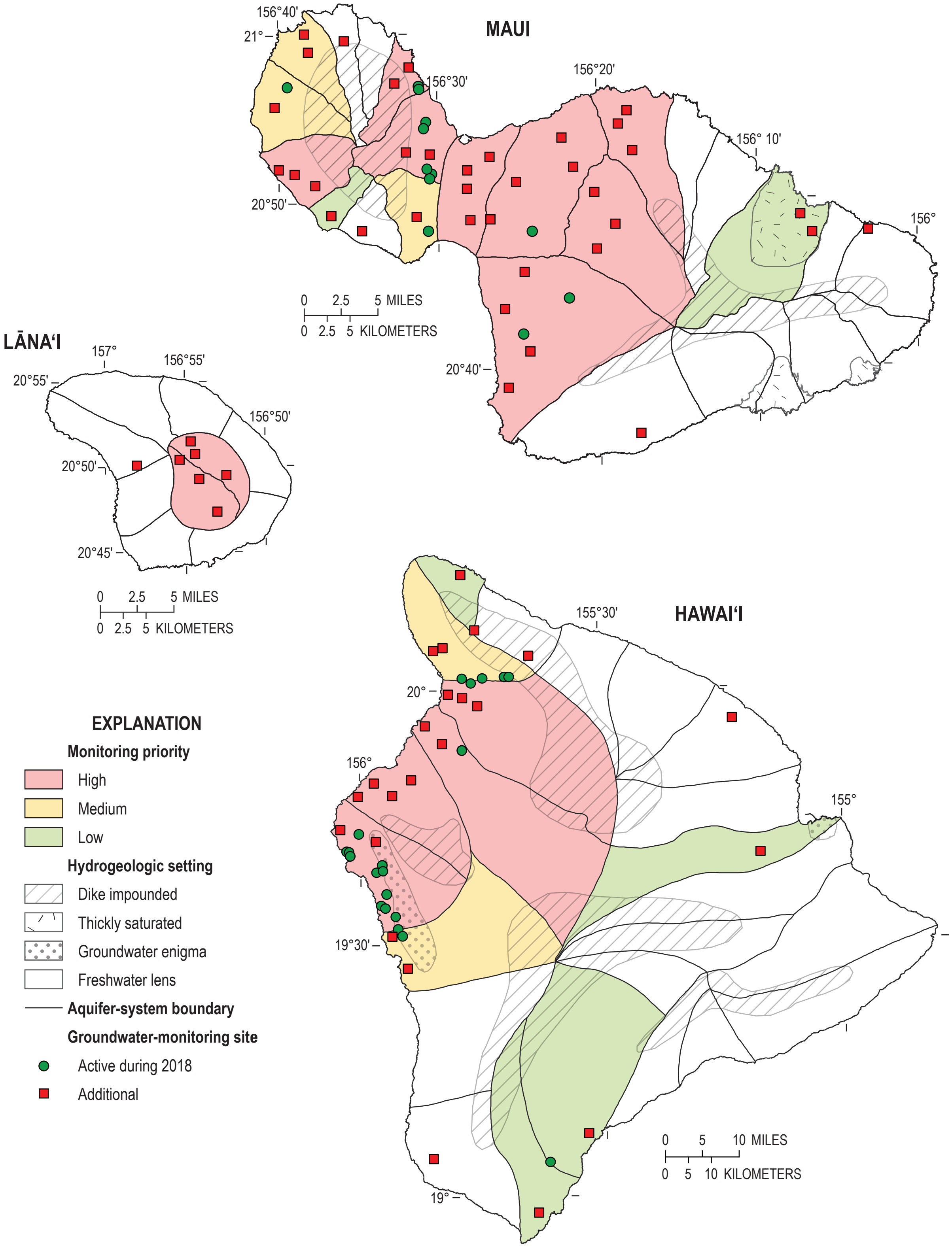


**Figure ES3.** —Continued

## Acknowledgments

Development of the water-resource monitoring program is conducted in cooperation with the State of Hawaiʻi Commission on Water Resource Management (CWRM) and in collaboration with the University of Hawaiʻi Water Resources Research Center (WRRC). The authors wish to thank the CWRM, WRRC, County water departments, and Hawaiʻi Department of Land and Natural Resources Division of Forestry and Wildlife in helping to identify current and future water-resource issues and monitoring needs for rainfall, surface-water, and groundwater resources in the State. The CWRM and Honolulu Board of Water Supply also helped to verify accuracy of current (2018) data-collection sites and define data-quality goals for anticipated uses of the data.

The authors are grateful to Lhiberty Pagaduan and Heather Jeppesen for the careful and meticulous review of the tables and figures in this report. The detailed review comments provided by Delwyn Oki, Marla Stuckey (USGS Pennsylvania Water Science Center), and Barry Hill (former USGS Pacific Islands Water Science Center Data Section Chief) helped to finalize the report.

# Contents

## Figures

## Tables

# Conversion Factors

U.S. customary units to International System of Units

| Multiply | By | To obtain |
|---|---|---|
| | Length | |
| inch (in.) | 25.4 | millimeter (mm) |
| foot (ft) | 0.3048 | meter (m) |
| mile (mi) | 1.609 | kilometer (km) |
| yard (yd) | 0.9144 | meter (m) |
| | Area | |
| acre | 4,047 | square meter ($m^2$) |
| acre | 0.004047 | square kilometer ($km^2$) |
| square foot ($ft^2$) | 0.09290 | square meter ($m^2$) |
| square mile ($mi^2$) | 2.590 | square kilometer ($km^2$) |
| | Volume | |
| gallon (gal) | 0.003785 | cubic meter ($m^3$) |
| million gallons (Mgal) | 3,785 | cubic meter ($m^3$) |
| cubic foot ($ft^3$) | 0.02832 | cubic meter ($m^3$) |
| cubic mile ($mi^3$) | 4.168 | cubic kilometer ($km^3$) |
| | Flow rate | |
| 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 ($m^3/d$) |
| cubic foot per second ($ft^3/s$) | 0.64636 | million gallons per day (Mgal/d) |
| gallon per day (gal/d) | 0.003785 | cubic meter per day ($m^3/d$) |
| million gallons per day (Mgal/d) | 0.04381 | cubic meter per second ($m^3/s$) |

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

$$°F = (1.8 \times °C) + 32$$

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

$$°C = (°F - 32) / 1.8$$

# Datum

Vertical coordinate information is referenced relative 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

| | |
|---|---|
| CTD | a probe that measures conductance, temperature, and depth |
| CWRM | State of Hawai‘i Commission on Water Resource Management |
| DHHL | Hawai‘i Department of Hawaiian Home Lands |
| DLNR | Hawai‘i Department of Land and Natural Resources |
| DMW | deep monitor well |
| DQO | data-quality objectives |
| DTW | depth to water |
| EMI | East Maui Irrigation |
| EPA | U.S. Environmental Protection Agency |
| GIS | geographic information system |
| HBWS | Honolulu Board of Water Supply |
| HC&S | Hawaiian Commercial and Sugar Company |
| HDWS | County of Hawai‘i Department of Water Supply |
| IVE | interpolated variance estimator |
| KIUC | Kaua‘i Island Utility Cooperative |
| MDWS | County of Maui Department of Water Supply |
| MP | measuring point |
| NAD83 | North American Datum 1983 |
| NIST | National Institute of Standards and Technology |
| NWIS | National Water Information System |
| PHMWG | Pearl Harbor Monitoring Working Group |
| QA/QC | quality assurance and quality control |
| RCP | Representative Concentration Pathway |
| SKN | State key number |
| TWI | trade-wind inversion |
| USGS | U.S. Geological Survey |
| WGS | World Geodetic System of 1984 |
| WMO | World Meteorological Organization |
| WRPP | Hawai‘i Water Resources Protection Plan |
| WRRC | Unversity of Hawai‘i Water Resources Research Center |

# Water-Resource Management Monitoring Needs, State of Hawai‘i

By Chui Ling Cheng,[1] Scot K. Izuka,[1] Joseph J. Kennedy,[1] Abby G. Frazier,[2] and Thomas W. Giambelluca[3]

## Abstract

In cooperation with the State of Hawai‘i Commission on Water Resource Management and in collaboration with the University of Hawai‘i Water Resources Research Center, the U.S. Geological Survey developed a water-resource monitoring program—a rainfall, surface-water, and groundwater data-collection program—that is required to meet State needs for water-resource assessment, management, and protection in Hawai‘i. Current and foreseeable issues related to water-resource management and climate-change effects guided the evaluation of data-collection sites within the monitoring program. Data-collection sites currently (2018) being operated in Hawai‘i were evaluated, and additional data-collection sites were selected on the basis of their usefulness for characterizing anthropogenic effects on water resources or representing natural conditions. Data-collection strategies consist of a combination of continuous long-term monitoring to evaluate trends and climate-change effects and occasional and periodic intensive monitoring to enhance spatial understanding of hydrologic conditions and to address current issues in priority areas—areas that currently have water-avail-ability issues or are expected to have the greatest socioeconomic or ecological effects because of climate change.

Priority areas for rainfall monitoring consist of urban and agricultural lands, areas with high rainfall and high-rainfall gradient, and areas within the trade-wind inversion band. Surface-water priority areas consist of streams with major surface-water diversions, with established interim instream-flow standards, in a surface-water management area, that support water leases, and with uncertainties in hydrogeologic characteristics. Priority areas for groundwater monitoring consist of areas with high withdrawal, declining water levels, reduced recharge, limited alternative sources, and uncertainties in hydrogeologic characteristics.

Data-quality objectives for the rainfall, surface-water, and groundwater monitoring programs that describe anticipated uses of the data were established with the goal of producing useful, reliable, and accurate water-resource information of sufficient precision to support decision making. The data-quality objectives also consider quality-assurance and quality-control programs that ensure defensible data. Establishment of common data-quality objectives not only assures comparability of data collected by multiple agencies but also allows data from academic, private, and public organizations to be useful for meeting State monitoring needs, provided the data meet appropriate data-quality objectives and data-accessibility requirements.

## Introduction

Concerns about the limitations of water-resource monitoring programs in Hawai‘i have prompted the U.S. Geological Survey (USGS) to evaluate the current (2018) water-resource monitoring program in the context of identified issues and new initiatives in water-resource management and potential hydrologic effects of climate change. In recent years, the limitations of water-resource monitoring networks have created challenges for water-resource management because of (1) a loss in the number of monitoring stations, (2) an insufficient number of monitoring stations with long period of record, and (3) an insufficient coverage to provide water-resource data at a resolution necessary to inform decision making. Furthermore, the lack of a consolidated database of water-resource information collected by various Federal, State, County, and local agencies poses a major challenge to integrated water-resource protection and management. Rising demand for freshwater, emerging regulatory developments, potential increased volatility in climate patterns and effects, and new data-delivery capabilities have increased the demand for accurate and timely water-resource information. Assessments of current and foreseeable water-resource needs and how well the current monitoring program accommodates those needs are critical for designing a robust water-resource monitoring program that effectively and strategically applies available funds and other resources to collecting reliable and relevant water-resource information.

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[2]East-West Center, Honolulu, Hawai‘i.

[3]Water Resources Research Center and Department of Geography and Environment, University of Hawai‘i at Mānoa, Honolulu, Hawai‘i.

The USGS water-resource monitoring program for Hawaiʻi consists of rainfall, surface-water, and groundwater data collected since the early 1900s, and it is complemented by water-resource data from other Federal, State, and County agencies, and academic institutions. The USGS monitoring program is funded in cooperation with many Federal, State, County, and local agencies; the State of Hawaiʻi Commission on Water Resource Management (CWRM) is the most significant funding partner supporting water-resource data collection. Individual monitoring stations within the program are supported for specific purposes related to water-allocation determination, reservoir operations, water-quality and water-quantity regulation requirements, and flood-hazard mitigation. Collectively, water-resource data collected as part of the program are critical for current hydrologic trend analysis and operational decisions, as well as long-term resource assessment, strategic planning, and infrastructure design.

The guiding principles of the USGS water-resource monitoring program are: (1) monitoring stations are funded by the USGS and cooperating agencies to achieve their respective monitoring goals; (2) data are available to the public and all cooperating agencies, typically in real time, at no cost through the USGS National Water Information System (NWIS) web interface (https://doi.org/10.5066/F7P55KJN; U.S. Geological Survey, 2018); (3) USGS operates the monitoring stations on behalf of all cooperating agencies, which achieves economies of scale by eliminating the need for multiple infrastructures for testing equipment, providing training to staff, developing and maintaining communications and database systems, and conducting data-quality control and assurance; and (4) USGS brings the capability of its national staff to bear on challenges such as responding to catastrophic floods or finding solutions to unique monitoring conditions. A number of State, County, and local agencies in Hawaiʻi collect data; however, not all data are reported with the same frequency and made publicly available, and some data may have greater uncertainties owing to disparate quality-assurance and -control processes. Consequently, some data may have limited value in addressing water-resource management issues.

## Previous Investigations

Water-resource monitoring programs must be evaluated periodically to determine their sufficiency in light of emerging water-resource information needs. In the 1970s and 1980s, evaluations of Hawaiʻi's water-resource monitoring program focused primarily on providing a statewide descriptive inventory of monitoring stations in operation and a statistical summary of available long-term records by island. In 1973, the State published a report containing the location information for all climate stations statewide (State of Hawaiʻi, 1973). Matsuoka (1981 and 1983) described available surface-water quality and quantity data for Kauaʻi, Oʻahu, Molokaʻi, Maui, and Hawaiʻi island through 1979 and noted significant surface-water diversions out of and inflows to gaged basins for the purpose of developing instream-use criteria and associated regulations. Miyamoto and others (1986) described available groundwater data for Oʻahu to support the USGS Regional Aquifer-System Analysis Program that was initiated in response to a Congress appropriations bill prompted by the 1977 drought (USGS, 1986). Giambelluca and others (1986; 2013) compiled and analyzed available rainfall data to develop mean and median monthly and annual rainfall maps for Kauaʻi, Oʻahu, Molokaʻi, Maui, Lānaʻi, and Hawaiʻi island. Only a few studies considered various facets of water-resource planning and management as principal criteria for evaluating the water-resource monitoring program (Yamanaga, 1972; Takasaki, 1977; Matsuoka and others, 1985).

The most recent evaluations of the USGS water-resource monitoring program in Hawaiʻi were in the 1990s. Fontaine (1996) evaluated rainfall and surface-water quantity and quality monitoring programs for Kauaʻi, Oʻahu, Molokaʻi, Maui, and Hawaiʻi island. The report provided a summary of the available data through 1994 and an assessment of whether the monitoring program addressed important water-resource issues identified by cooperating agencies and stakeholders at the time of study. Many of the water-resource issues identified in Fontaine (1996) continue to guide the current and future water-resource data-collection efforts. Anthony (1997) evaluated the groundwater monitoring program for Kauaʻi, Oʻahu, Molokaʻi, Maui, and Hawaiʻi island in 1992. The evaluation was based on the usefulness of the monitoring program to define seasonal and long-term changes in groundwater levels and chloride concentrations induced by human-related and natural stresses. Wells that help determine the response of groundwater-flow systems to human-induced stresses were grouped into the water-management network, whereas wells that help determine the response of groundwater-flow systems to natural stresses for different climatic and hydrogeologic settings were grouped into the baseline network. The concept of the water-management and baseline networks described by Anthony (1997) was modified from Heath (1976) and Reilly (1993), and it is used in this report to guide evaluation of the water-resource monitoring program in 2018.

Water-resource data collected over the years have supported studies critical to understanding the hydrology of Hawaiʻi. Results of these studies are important inputs to decision-support tools for water-resource management. Studies that evaluate long-term trends in streamflow and groundwater storage help to determine how climate-change affects water resources. Studies that describe streamflow characteristics help determine streamflow availability during low-flow conditions. Water-resource data are also used in watershed, groundwater, and water-budget models to identify critical areas where water-resource protection efforts can be targeted. As new water-resource issues emerge, the monitoring programs should be adaptively modified to meet monitoring needs.

## Water-Resource Issues

The CWRM identified 10 key water-resource issues in Hawaiʻi, gathered from public and stakeholder meetings, as

part of the Hawaiʻi Water Resources Protection Plan, hereafter referred to as 2019 WRPP (State of Hawaiʻi, 2019c, p. 13–21). For the purpose of designing a monitoring program, some of these broader issues were distilled into specific goals of the water-resource monitoring program. The 10 key issues are summarized as follows:

1. Reliable, long-term data coupled with accurate accounting of water use are needed for water-resource management.
2. Increasing competition for water resources in certain areas calls for aggressive conservation measures to ensure effective use of available water resources.
3. Protection of water resources for public-trust purposes has been difficult owing to a lack of consolidated information pertaining to the public-trust purposes, especially information on traditional and customary practices.
4. Aging and inefficient infrastructure could potentially affect the quality and quantity of available water resources.
5. Climate change is expected to increase water demand and decrease water availability, and continued research is needed to refine climate-change effects.
6. Land-use changes are increasing the potential for contamination of available freshwater supplies.
7. Land-use changes are reducing freshwater recharge.
8. As beneficiaries of the public trust and users of water resources, communities feel uninformed and underrepresented in water-resource management and decision making.
9. Violations to the State Water Code should be thoroughly investigated, fair penalties enforced, and corrected in a timely manner. Enforcement policy and priorities should be clear, effective, and open for refinements.
10. Water-resource issues are complex, and effective management of water resources require an integrated effort from a diverse group of individuals and entities.

These water-resource issues, although general in nature, helped to further identify issues specific to surface-water and groundwater resources that were subsequently used to develop a set of criteria for evaluating the data-collection sites in the water-resource monitoring program.

## Purpose and Scope

This study is conducted in cooperation with the CWRM and in collaboration with the University of Hawaiʻi Water Resources Research Center (WRRC) to aid in the management of water resources in Hawaiʻi as it fulfills the 2019 WRPP Action Plan, Goal 1, Project 1.1, Task 1.1.1 (State of Hawaiʻi, 2019c, p. 59–60). The objective of this study is to develop a water-resource monitoring program, specifically a rainfall, surface-water, and groundwater data-collection program, that meets State monitoring needs for water-resource assessment, management, and protection. The study scope comprises the six Hawaiian Islands of Kauaʻi, Oʻahu, Molokaʻi, Maui, Lānaʻi, and Hawaiʻi—Niʻihau and Kahoʻolawe were excluded from the study scope but may be included in future assessments when water-resource needs are identified. A series of workshops were held in collaboration with the CWRM, County water departments, and other stakeholders to identify current and foreseeable issues related to water-resource management and climate change. Subsequently, these issues were used to develop a set of criteria for evaluating data-collection sites within the water-resource monitoring program and a set of goals the collective monitoring program should achieve.

This assessment did not consider water-resource monitoring needs related to water-quality or to flood-hazard mitigation because the Hawaiʻi Department of Health is responsible for identifying State water-quality monitoring needs, and flooding is not a water-resource availability and allocation issue. Therefore, the water-resource monitoring program did not include monitoring stations established solely for collecting water-quality information and peak-flow information (crest-stage stations and stations that only monitor gage height in a stream or reservoir). However, some of the data collected as part of the monitoring program may support water-quality determinations and flood-frequency analyses.

Following the discussion on the geographical setting of the Hawaiian Islands, the report is organized into three sections, one section for each water-resource monitoring program: rainfall, surface water, and groundwater. Each section includes a discussion on (1) current water-resource issues, (2) data-collection strategies, (3) monitoring needs identified during the stakeholder workshops, (4) the current (2018) water-resource program, and (5) the water-resource monitoring program needed for addressing State needs. Data-quality objectives and limitations of the monitoring programs are presented at the end of the report.

# Setting

Hawaiʻi is a group of islands in the northern tropics of the central Pacific Ocean (fig. 1). The islands considered for the monitoring program are the six largest in the group and constitute 98 percent (6,305 square miles [$mi^2$]) of the total land area in the archipelago. The islands range in size from 141 $mi^2$ (Lānaʻi) to 4,039 $mi^2$ (Hawaiʻi island) and the peak altitude of each island ranges from 3,366 feet (ft) (Lānaʻi) to 13,796 ft (Hawaiʻi island). Oʻahu (599 $mi^2$) is the most densely populated of the islands—about 70 percent of Hawaiʻi's population of 1.4 million lives on Oʻahu (State of Hawaiʻi, 2019a).

## Climate

The climate of Hawaiʻi results from the interaction of oceanic and atmospheric processes with the islands' landforms. Because of its tropical latitude, the predominant winds in

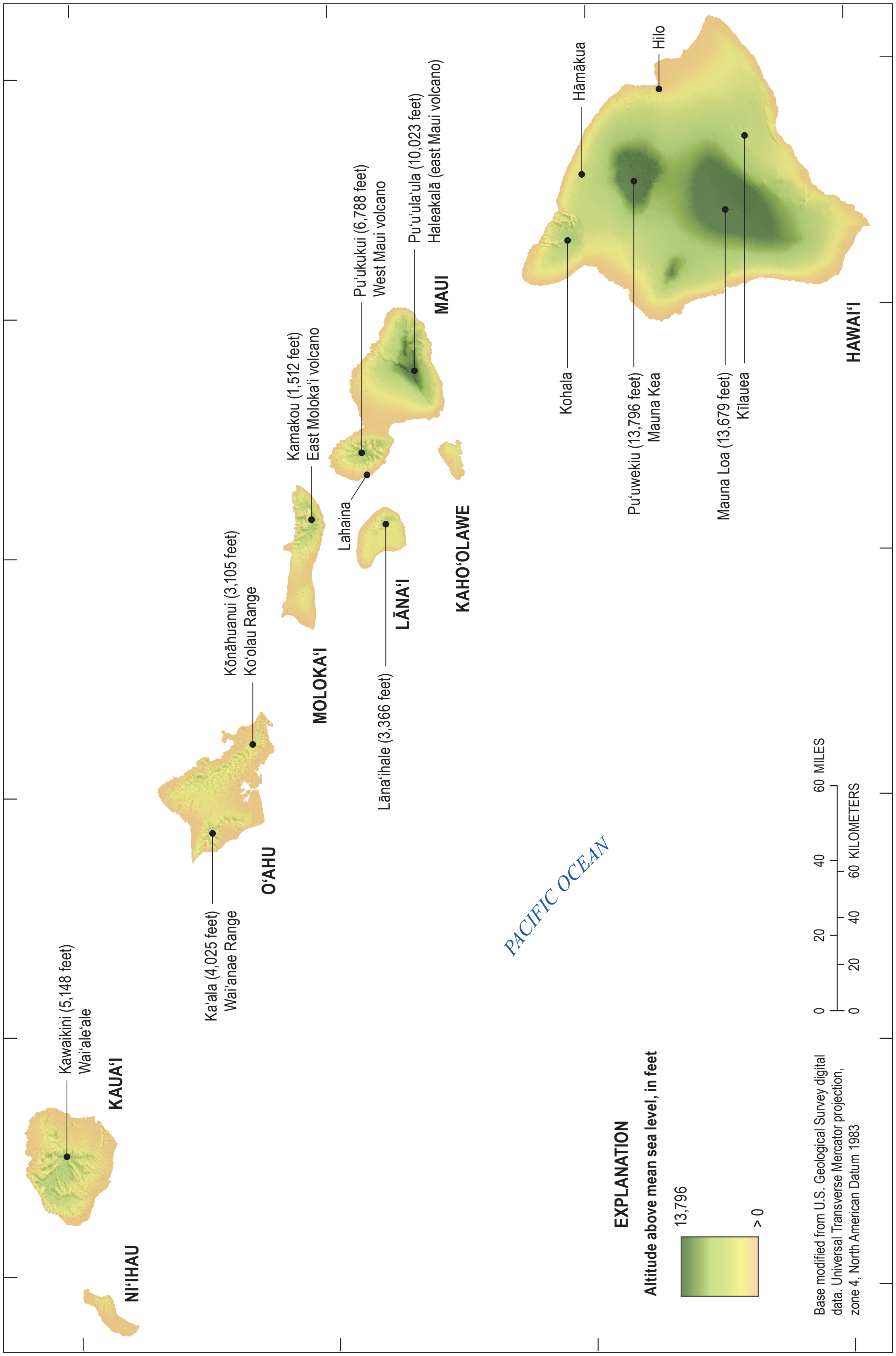



**Figure 1.** Map of the Hawaiian Islands showing the general topography of individual islands.

Hawaiʻi are northeasterly trade winds (Blumenstock and Price, 1967; Schroeder, 1993; Garza and others, 2012). Spatial patterns of climate are extremely diverse owing to the topography, producing a wide range of climate types, including deserts, humid tropical rain forests, and alpine tundra on the mountain peaks (Giambelluca and Schroeder, 1998). These factors define the primary physiographic zones, which are windward (northeast-facing slopes) and leeward (southwest-facing slopes), for the islands included in the water-resource monitoring program (fig. 2). Windward areas are generally cooler and wetter, whereas leeward areas are hotter and drier.

Most precipitation in Hawaiʻi is in the form of rain, although fog interception and snow are important in some areas (Juvik and others, 2011; Martin and others, 2019). Rainfall distribution in Hawaiʻi is controlled mainly by orographic lifting. As the prevailing northeasterly trade winds encounter the mountain slopes of the islands, air carrying moisture from the ocean is driven to higher altitudes. The rising air cools adiabatically, and the water vapor it carries condenses, producing clouds and, eventually, rainfall. As a result, rainfall generally is high over mountain crests and in windward areas, and low in leeward areas (fig. 2). Mean annual rainfall ranges from less than 10 inches on some leeward coasts to over 400 inches on some windward slopes (Giambelluca and others, 2013). Leeward areas of Hawaiʻi island are an exception, where a local area of higher orographic rainfall at middle altitudes is generated by trade winds that wrap around Mauna Loa and by sea breezes related to the diurnal heating and cooling of the island's large landmass. Orographic lifting is limited to about 7,200 ft altitude by a temperature inversion known as the trade-wind inversion (TWI; Longman and others, 2015). The TWI caps cloud growth and causes low-rainfall conditions at the peaks of the highest mountains—Haleakalā, Mauna Kea, and Mauna Loa (fig. 1). Mid-latitude and tropical storm systems also bring rain to the islands and are the main sources of rainfall in the drier areas of the islands (Giambelluca and others, 2013). In the drier leeward areas, rainfall is greater in the winter wet season (November to April) when storms are more frequent, and lesser in the summer dry season (May to October). In contrast, seasonal variation is less distinct on wet windward areas, where orographic rainfall is abundant throughout the year. In the mid-altitudes in the leeward areas of Hawaiʻi island, rainfall is greater in the summer when the diurnal sea breezes are stronger (Giambelluca and others, 2013).

Rainfall in Hawaiʻi also varies because of multiyear variations linked to oceanic and atmospheric climate cycles such as the El Niño-Southern Oscillation, which recurs at a frequency of about 3 to 7 years and has events that last about 0.5 to 1.5 years, and the Pacific Decadal Oscillation, which shifts in phase every 20 to 30 years. These sources of variability cause some years to be wetter or drier than the long-term average (Chu and Chen, 2005; Frazier and others, 2018). Rainfall data show a long-term average drying trend for Hawaiʻi over the last century (Kruk and Levinson, 2008; Frazier and Giambelluca, 2017), and streamflow-gaging station data show a concurrent downward trend in base flow (Oki, 2004; Bassiouni and Oki, 2013). Global changes in climate are likely to affect future climate in Hawaiʻi. Recent statistical downscaling of global model projections indicates that wet windward slopes of mountainous areas will become wetter or remain unchanged, whereas the dry leeward areas will become drier (Elison Timm and others, 2015). However, projections of future rainfall in Hawaiʻi vary widely and are currently the subject of active research.

## Hydrogeology

The islands of Hawaiʻi are the subaerial parts of enormous basaltic shield volcanoes that were built on the northwestward-moving Pacific lithospheric plate by hot-spot volcanism (Macdonald and others, 1983). Subaerial parts of individual islands consist of one to five volcanoes. Most of the volume (90 percent or more) of a shield volcano is formed during the shield stage, which is characterized by voluminous eruptions of fluid basaltic lava (Clague and Dalrymple, 1987). The eruptions form a large dome-shaped volcano built of thousands of thin lava flows. Most shield-stage eruptions occur at the summit or along rift zones of the shield volcano. The pile of lava flows that form during this stage create permeable aquifers that are among the most productive in Hawaiʻi, including the aquifers that supply most of the water to the densely populated island of Oʻahu (Izuka and others, 2018). Some shield volcanoes have transitioned into or passed through a postshield stage, and some have transitioned further into a rejuvenation stage. Rocks from these stages constitute only a few percent of the islands' volume and, in general, form aquifers that are less permeable than shield-stage, lava-flow aquifers. Even so, postshield and rejuvenation-stage rocks have been developed for groundwater resources on some islands and can affect the flow of groundwater in the more permeable shield-stage aquifers they overlie.

Eruptions are fed by magma rising though fractures in the subsurface. Magma that does not reach the surface solidifies in the fractures and forms dense, sheet-like bodies of rock, known as dikes, that cut across the stack of lava flows of the shield volcano. Dikes are most densely clustered beneath the summit or along the rift zones of the shield volcano. Dikes usually have much lower permeability than the shield-stage lava flows they intrude and can impede groundwater flow.

Stream erosion and mass wasting have cut narrow gullies that have deepened and widened over time to form amphitheater-headed valleys (Macdonald and others, 1983). In some places, erosion and faulting have exposed the volcanoes' interior structure, including dikes (Macdonald and others, 1983). Evidence of stream erosion is less extensive on younger shield volcanoes.

Lower sections of larger valleys have been partly filled with alluvium and marine sediment. The valley fill can extend to depths below present sea level. On older islands, particularly Oʻahu, thick deposits of sediments form an extensive coastal plain that nearly encircles the island. Sedimentary deposits—particularly the clay-matrix alluvium derived by erosion of basalt—are generally less permeable than aquifers formed by shield-stage lava flows.

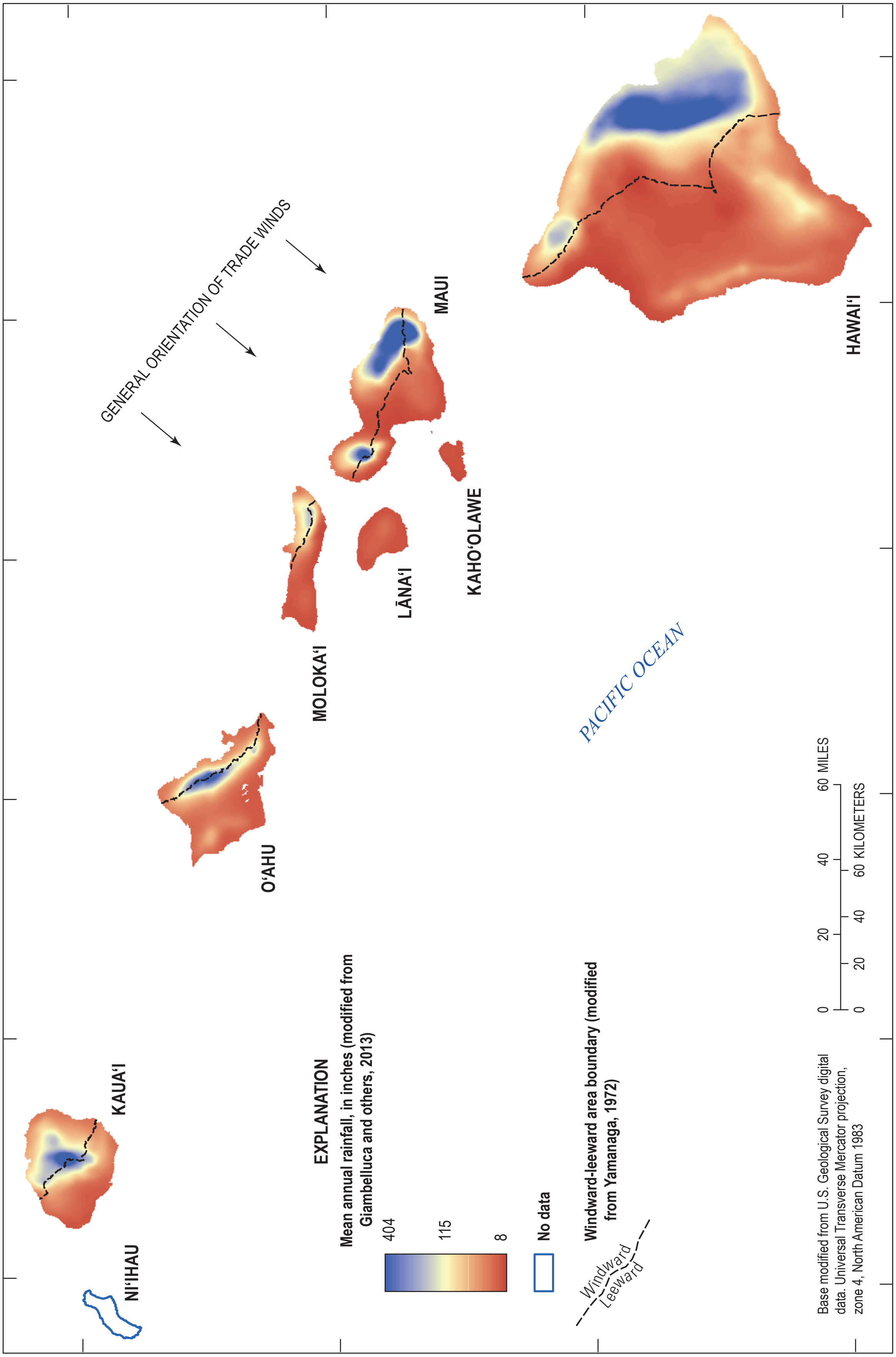



**Figure 2.** Map of the Hawaiian Islands showing mean annual rainfall in each island, excluding Ni‘ihau.

## Surface Water

Streams play a critical role in shaping the unique landscape of the Hawaiian Islands because they are the predominant surface-water body type. Throughout the geomorphic evolution of the islands, streams carved amphitheater-headed valleys, and transported and deposited sediments to various parts of the valleys and offshore waters. Originating from interior mountainous areas and terminating at the coast, streams form a radial drainage pattern across the islands, and density of the stream channels decreases with decreasing altitude. Individual valleys are more deeply incised in the geologically older islands, especially on windward slopes where rainfall greatly contributes to the erosive power of the streams that expose the complex stratigraphy of the shield volcano along valley walls.

Streamflow is highly variable in space and time, which is attributed to the variability in rainfall and geology. Most drainage basins in Hawai‘i are relatively small, averaging about 11 $mi^2$ in area, and have steep gradients with little channel storage. As a result, Hawaiian streams respond quickly to rainfall, and during rainfall periods, streams can transition from base flows to flood flows in less than an hour. In general, streams often flow perennially in the windward areas where flow is supported by persistent rainfall and groundwater recharge, and streams in the leeward areas are intermittent when rainfall is low. Ephemeral streams flow only in response to heavy rainfall and typically occur in the dry leeward areas. Natural base flow in streams is chiefly derived from groundwater sources and can vary along the length of the stream channel. Dike-impounded groundwater maintains perennial flow in some streams at the high-altitude reaches where the streams intersect the dike-impounded-groundwater body. These stream reaches are called “gaining reaches” because groundwater contributes to streamflow. In stream valleys where extensive erosion has exposed dike compartments, groundwater from these dike-impounded systems commonly discharges directly to streams. Downstream from the area of dike-impounded groundwater, the water table is typically below the streambed. As a result, the mid-altitude reaches commonly are called “losing reaches” because streamflow discharges to the groundwater body. Most low-altitude reaches maintain perennial flow where the freshwater lens discharges near the coast, although some streams may lose all flow to the groundwater body before reaching the ocean during low-rainfall periods.

Streams provide a vital source of water for the islands’ inhabitants. Traditionally, stream water was used to cultivate wetland kalo (taro), a Hawaiian staple and core of the Hawaiian culture. The ‘auwai (irrigation ditch) transports water from the stream to irrigate each lo‘i (kalo terrace), and then returns flow to the stream. Kalo is still actively cultivated in many parts of the islands. Streams in Hawai‘i were previously diverted to support sugarcane plantations, which built extensive gravity-fed ditch and tunnel systems to collect stream water from the wet mountainous interior areas and to convey that water to irrigate fields at lower altitudes. These large-engineered surface-water diversion systems altered drainage patterns within basins by transporting water within and across drainage basin boundaries. Some streams were used to convey diverted water from one part of the diversion system to the next to maximize diversion capacity and lower infrastructure costs. When plantation agriculture subsided in the latter part of the 20th century, diversions previously used for sugarcane cultivation were shifted to support diversified agriculture and other uses.

## Groundwater

Hawai‘i’s aquifers provide freshwater for residents, diverse industries, and a large part of the U.S. military in the Pacific Ocean region. The aquifers also provide natural freshwater discharge to streams, springs, wetlands, and the coast that support cultural practices, aesthetics, recreation, and ecosystems. Each island is surrounded by seawater, and all fresh groundwater in Hawai‘i’s aquifers ultimately comes from precipitation. Some of the water from precipitation runs off the land surface to the ocean through streams or returns to the atmosphere through evapotranspiration; the remainder recharges groundwater (fig. 3). Water diverted from streams or pumped from groundwater for irrigation may also contribute to groundwater recharge, but even this water ultimately originates as precipitation.

Most groundwater in Hawai‘i occurs in one of four principal hydrogeologic settings: (1) freshwater lens in high-permeability aquifer, (2) dike-impounded groundwater, (3) thickly saturated low-permeability aquifer, and (4) perched groundwater (Izuka and others, 2018). For brevity in this report, these settings will be referred to as the (1) freshwater-lens setting, (2) dike-impounded-groundwater setting, (3) thickly saturated setting, and (4) perched-groundwater setting, respectively. Conceptual diagrams of the hydrogeologic settings are shown in figure 4.

*Freshwater-Lens Setting*—In the high-permeability aquifers formed by dike-free shield-stage lava flows, fresh groundwater forms a lens-shaped body that buoyantly overlies denser saltwater from the ocean (fig. 4*A*). Because the high-permeability aquifer offers little resistance to groundwater flow, the lens has a low-altitude water table with a gentle seaward gradient. The lens is bounded below by a brackish transition zone. The lens receives water from recharge and from subsurface flow from upgradient aquifers. Groundwater in the lens flows toward the coast, where it naturally discharges to springs, streams, wetlands, and submarine seeps. In some older islands, particularly O‘ahu, low-permeability coastal sediments form a semiconfining unit, known as caprock, that partly overlies the high-permeability aquifer and impedes the natural discharge of groundwater near the coast. As a result, the freshwater lens is thicker than it would be without the caprock. Where caprock extends above sea level, some groundwater discharges at higher altitudes and farther inland, resulting in increased groundwater discharge to streams and springs above sea level.

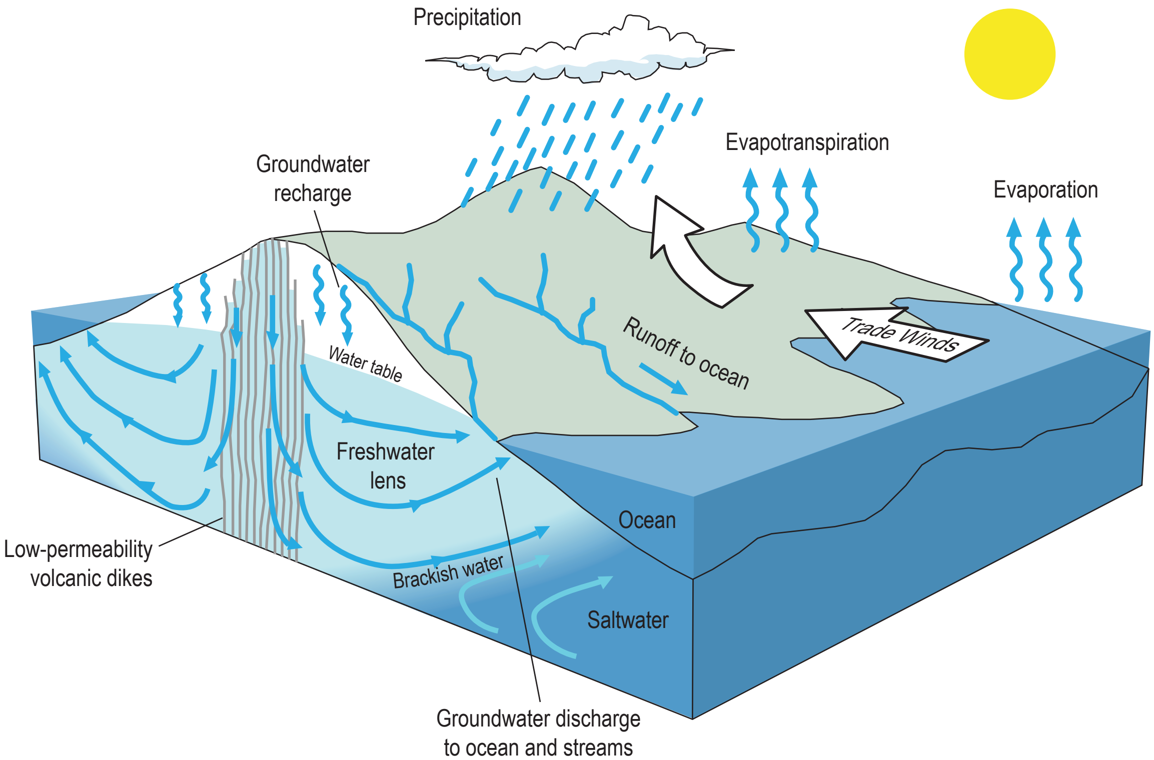



**Figure 3.** Diagram showing the relation of fresh groundwater to precipitation, evapotranspiration, runoff, and saltwater from the ocean in the Hawaiian Islands. Image from Izuka and others, 2018.

In younger islands with high-permeability aquifers where the caprock is thin or absent, the freshwater lens is thin and, in some areas, brackish water may exist immediately below the water table.

*Dike-Impounded-Groundwater Setting*—Low-permeability dikes that intrude the high-permeability lava-flow aquifer form compartments in which groundwater can be impounded to hundreds or thousands of feet above sea level (fig. 4*B*). Inflow to the compartments is mostly from recharge through the ground surface. Water flows from compartments with higher water levels to compartments with lower water levels, and eventually to adjacent groundwater bodies—such as freshwater lenses—or discharges to springs, streams, and submarine seeps. In younger islands where most dikes remain unexposed by erosion, groundwater flow between dike compartments occurs in the subsurface. Where erosion and faulting have breached the dike compartments, much of the groundwater discharges to springs and streams. Fresh groundwater in most dike compartments probably extends several thousand feet below sea level.

*Thickly Saturated Setting*—Some lava-flow aquifers have low permeability. On eastern Kaua‘i, the low permeability results from the accumulation of thick rejuvenation-stage lava flows in depressions formed by erosion and faulting of the shield volcano. Because of the aquifer’s low permeability and eastern Kaua‘i’s wet climate, a thick part of the aquifer is saturated with fresh groundwater (a condition herein referred to as a thickly saturated setting; fig. 4*C*). Groundwater saturates nearly to the land surface, and the water table is kept just below most of the land surface by streams that drain the upper saturated part of the aquifer. As a result, most groundwater flowing through the aquifer discharges above sea level to streams rather than below as submarine groundwater discharge. The thick fresh groundwater body may be underlain by a transition zone and saltwater near the coast, but farther inland, where the water table is hundreds of feet above sea level, the freshwater body probably extends thousands of feet below sea level.

*Perched-Groundwater Setting*—Perched groundwater is a body of saturated groundwater that occurs above another saturated groundwater body (such as a freshwater lens) and is separated from the lower body by unsaturated rock. The perched groundwater body is held up or “perched” by a low-permeability layer embedded within a body of higher permeability rock (fig. 4*A*). Perched groundwater may discharge to springs or streams, but most of it continues downward to the freshwater lens. Most groundwater bodies described as perched are small, although relatively extensive areas of high-altitude water levels on Maui and Hawai‘i island have been attributed to perched bodies.

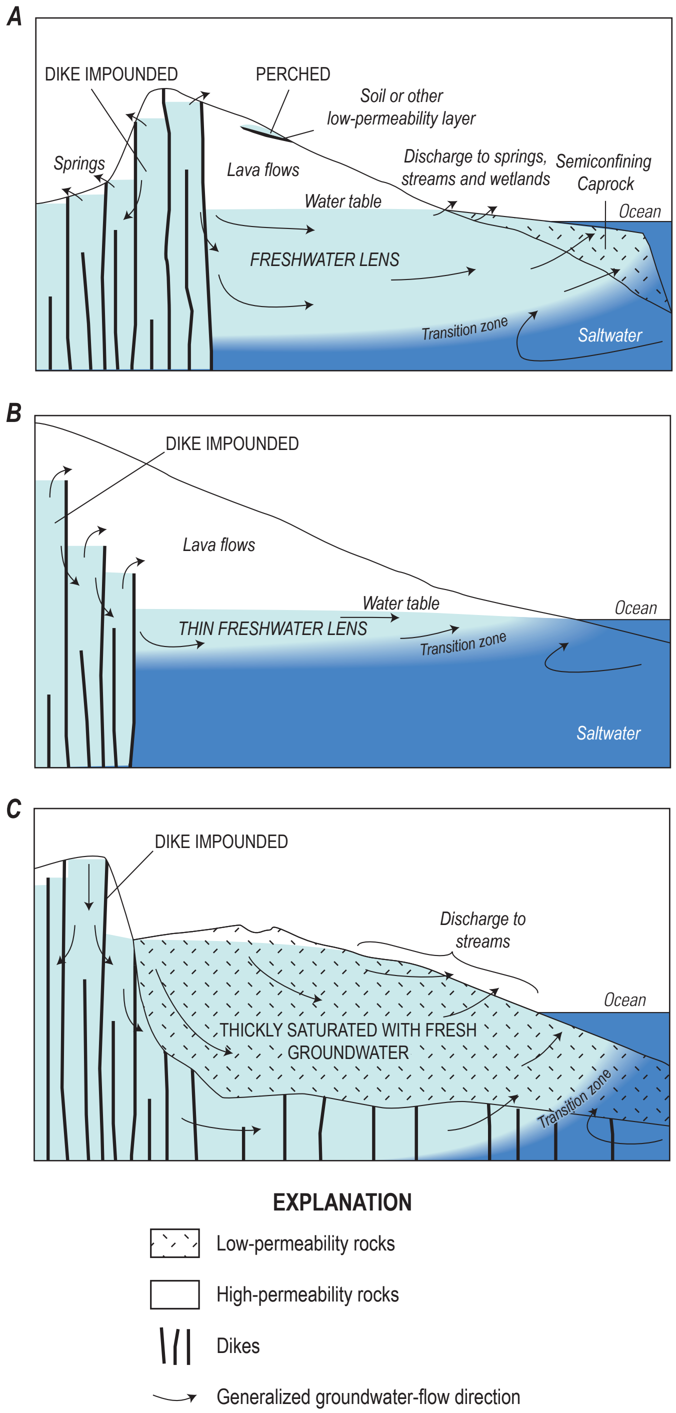



**Figure 4.** Diagrams showing conceptual models of groundwater occurrence and flow in Hawai'i. *A*, General conceptual model from about the early to middle 20th century. *B*, Conceptual model of a young shield volcano with no confining caprock, and where most dikes have not been exposed by erosion. *C*, Conceptual model for areas with substantial low-permeability rock and a thick freshwater lens. From Izuka and others (2018).

*Groundwater Enigmas*—Some occurrences of groundwater in Hawai‘i do not fit into any of the four settings presented above, and the hydrogeologic conditions responsible for these enigmatic occurrences are not completely understood. For example, high-altitude groundwater bodies in central O‘ahu and west Hawai‘i island are fully saturated (not perched) below the water table, but anomalous considering the high permeability of the aquifers and the lack of identifiable groundwater-impounding structures, such as dikes (Izuka and others, 2018). Another example occurs in aquifers in which two or more bodies of freshwater or brackish water are interlayered with saltwater, such as in Hilo (fig. 1; Thomas and others, 1996; Stopler and others, 2009) and the western coast of Hawai‘i island (Tillman and others, 2014). In Hilo, at least one of the deeper freshwater bodies has been attributed to confining by a soil layer between overlying Mauna Loa and underlying Mauna Kea strata (Thomas and others, 1996). The cause of the condition in west Hawai‘i island is not definitively known.

## Land Use and Land Cover

Changes in land use and land cover can have a substantial effect on water resources. Different types of land cover have different rates of evapotranspiration, cloud-water interception, runoff, and groundwater recharge. Different types of land use have different rates of water use. Irrigation of crops, parks, and golf courses redistribute the natural occurrence and flow of surface water and groundwater.

Since their first arrival about A.D. 300–700, humans have altered land cover in Hawai‘i by introducing plants and animals, clearing forests, and diverting stream water for crop irrigation (Newman, 1972; Kirch, 1982, 1998, 2000; Cuddihy and Stone, 1990). Large-scale monocrop agriculture, particularly sugarcane, emerged about the middle of the 19th century and grew to dominate agriculture in Hawai‘i by the 20th century. Sugarcane plantations diverted hundreds of millions of gallons of water per day from streams for irrigation and processing (Wilcox, 1996). The sugarcane plantations in Hawai‘i began declining in the late 20th century and by 2016, all sugarcane plantations throughout Hawai‘i had closed. These land-use changes constitute substantial alteration of the distribution of surface water and groundwater in Hawai‘i.

The resident population in Hawai‘i increased from 154,001 in 1900 (State of Hawai‘i, 2001) to about 1.4 million in 2010 (U.S. Census Bureau, 2011). Population increase and commensurate increases in urbanization and demand for water resources are likely to affect water resources in the future.

# Approach

Effective water-resource assessment, management, and protection require an understanding of seasonal and long-term hydrologic changes induced by human-related stresses and natural stresses. To understand these changes, data-collection strategies and sites were selected on the basis of their

usefulness for characterizing anthropogenic effects on water resources or representing natural conditions. Data-collection sites were grouped into two types of data-collection networks: (1) a resource-management network to determine effects of water- and land-use changes on water resources, and (2) a climate-response network to determine effects of climate change on water resources in representative climatologic and hydrogeologic settings. Data-collection sites in the resource-management network typically are located in areas subject to anthropogenic effects, such as stream diversions, groundwater withdrawals, or land-cover change. Conversely, data-collection sites in the climate-response network typically are located in areas free from anthropogenic effects. With this framework in mind, the evaluation of water-resource monitoring needs in Hawai‘i, pertaining to rainfall, surface water, and groundwater, followed four major steps:

1. **Determine current water-resource issues and priority areas for data collection.** Current issues and priority areas for rainfall data collection were identified as areas that currently have water-availability issues or are expected to have the greatest socioeconomic or ecological effects because of climate change. A series of five workshops were held in collaboration with the CWRM, County water departments, and other stakeholders to identify current issues and priority areas for data collection with respect to surface-water and groundwater resources. General water-resource issues outlined during the workshops helped to further identify issues specific to surface water and groundwater that were subsequently used to develop a set of criteria for evaluating the data-collection sites.

2. **Describe data-collection strategies.** Data-collection strategies consist of a combination of long-term monitoring to evaluate trends and climate-change effects and occasional intensive monitoring to enhance spatial understanding of hydrologic conditions and to address current water-resource issues in priority areas. The data-collection frequency of the different strategies was defined.

3. **Determine rainfall, streamflow, and groundwater data-collection sites needed to support the monitoring program.** Data-collection sites currently (2018) being operated in Hawai‘i that meet criteria for inclusion in the monitoring program were summarized. To supplement the current program, additional data-collection sites were selected with consideration given to reactivating discontinued sites with substantial historical data. The selection of currently active and additional data-collection sites for inclusion in the monitoring program was accomplished with input and guidance from the CWRM, WRRC, County water departments, and other stakeholders to ensure that State monitoring needs for water-resource assessment, management, and protection are met. The water-resource monitoring program should be periodically reevaluated to ensure that it addresses water-management needs when new hydrologic issues emerge in the future.

4. **Define data-quality objectives (DQO) for the monitoring program.** A meeting was held with the CWRM to define general DQO through outlining the various uses of water-resource data and determining the quality of the data needed for the different data uses. The DQO are included in this report to serve as guidelines for producing useful, reliable, and accurate water-resource information of sufficient precision to support decision making. These guidelines can be used to evaluate the quality of the data collected by all Federal, State, and County agencies, and determine whether the data meet program standards. Data collected from the monitoring program should be made publicly available to allow for integrated water-resource protection and management.

# Rainfall

Rainfall data collection in Hawai‘i began in the 1800s when most of the rain gages were operated by agriculture plantations and ranches to determine water availability (Giambelluca and others, 2013). The number of rain gages steadily increased, peaking in the late 1960s to early 1970s when close to 1,000 rain gages were in operation (Fontaine, 1996; Giambelluca and others, 2013). As plantation agriculture began to decline in the late 1970s, the number of active rain gages in Hawai‘i dropped rapidly. As of January 1, 2017, a total of 383 rain gages were in operation on Kaua‘i, O‘ahu, Moloka‘i, Lāna‘i, Maui, and Hawai‘i island (modified from Longman and others, 2018). Two rain gages were later destroyed by the 2018 lower east rift zone eruption of Kīlauea on Hawai‘i island (Neal and others, 2019). The remaining 381 rain gages exist within 16 different climate-data groups that serve the diverse meteorological needs of rainfall data across the State, 21 of which are operated by the USGS (see Longman and others [2018, table 1] for a description of the number of gages, types of meteorological observations, and measurement intervals that each climate-data group collects).

## Data Needs

Rainfall is the main source of surface water and groundwater in Hawai‘i. Rainfall data are often needed in models used to provide estimates of surface-water and groundwater availability for water-resource management decisions. A rise in demand for water supply resulting from population growth and the potential for altered rainfall patterns from climate change—alterations in intensity and total amounts (Chu and others, 2010; Frazier and Giambelluca, 2017)—create an expansive need for accurate rainfall data with a long period of record to understand, manage, and adapt to changes in water availability (Wilhite and Glantz, 1985).

Rainfall data are commonly used to determine the amount of water crops have received and whether irrigation is needed to supplement rainfall to meet biological requirements (Nawaz and others, 2015). In urban areas, rainfall-intensity and -duration data are used by engineers to design infrastructure capable of handling storm-induced high-flow events (Paixao and others, 2011). Rainfall data with a long period of record provide context for evaluating drought conditions (Keyantash and Dracup, 2002), calculating return frequencies of extreme events, and identifying long-term trends due to climate change (Frazier and others, 2018). Rainfall data are also foundational to hydrologic models that facilitate the characterization of regional water availability (Jayakrishnan and others, 2005), rainfall-runoff relations (Andreassian and others, 2001), and recharge rates to aquifer systems (Johnson and others, 2014).

## Data-Collection Strategies

Rainfall is commonly expressed as the depth of water that would cover a horizontal surface. The commonly used rainfall statistics are those that describe the mean or median tendency of rainfall at any given location (Giambelluca and others, 1986). An interpolation method must be used to create spatially continuous gridded rainfall data that characterize the rainfall distribution at different time intervals (Frazier and others, 2016; Giambelluca and others, 2013; Longman and others, 2019). These statistics are inherently uncertain because of the geostatistical interpolation methods used (Lopez and others, 2015). The high spatial variability and temporal variability of rainfall in Hawai‘i create a need for a rainfall-monitoring program that consists of rain gages with long periods of record and appropriate spatial distribution that characterizes conditions in rainfall priority areas and facilitates the development of accurate gridded datasets (Frazier and others, 2016).

### Long-Term Monitoring

Estimating the central tendency of rainfall at a location requires data with a long period of record to reduce the uncertainty caused by the temporal variability of rainfall. The World Meteorological Organization (WMO) initially recommended a period of record of 30 years for calculating rainfall statistics (WMO, 2018). However, this recommendation was made at a time when only 30 years of data were the maximum number of years available. Whereas this length of time is still the standard, it has become widely understood that a period of record substantially greater than 30 years is needed to develop statistically robust gridded datasets (WMO, 2018). Data with a long period of record increase the confidence in rainfall statistics and provide adequate historical context for water-resource managers and decision makers (Jones and others, 2009). This data-collection strategy is the key to an effective rainfall-monitoring program because it facilitates the evaluation of short-term shifts in rainfall that can lead to drought conditions or long-term trends associated with a changing climate.

### Rain-gage Density and Distribution

Appropriate rain-gage density and distribution are important for determining the spatial patterns of rainfall across a region, especially within a topographically diverse area, such as the Hawaiian Islands. Rainfall in Hawai‘i has extreme spatial variability owing to a combination of large topographic complexity and the prevailing northeasterly trade winds. One of the most dramatic rainfall gradients in Hawai‘i can be found on Maui, where the rain gage on the summit of Pu‘ukukui on west Maui has an annual rainfall of 366 inches (9,296 millimeters [mm]), whereas a rain gage located approximately 4 miles (6.4 kilometers [km]) southwest receives only 15 inches (381 mm) of rain annually (Giambelluca and others, 2013), which produces a rainfall gradient of more than 87 inches per mile (1,390 mm per km). Spatially representative rainfall data are critical for developing reliable gridded datasets that accurately characterize the range of rainfall gradients found across Hawai‘i. As rain-gage density in an area increases, uncertainty in the interpolation method decreases, thus reducing the amount of uncertainty in gridded datasets and subsequent ecological and hydrological model outputs (Mishra and Coulibaly, 2009). Although an ideal rain-gage density is not easily quantifiable, there are general guidelines for different climatic and geographic regions. The recommended guideline for a minimum rain-gage density on small mountainous islands (less than 7,722 $mi^2$) is one rain gage for every 9.65 $mi^2$ (25 square kilometers [$km^2$]) of land (WMO, 1965). However, this recommendation is insufficient for urban areas, which have a recommended rain-gage density of one rain gage for every 3.9–7.7 $mi^2$ (10–20 $km^2$) of land (WMO, 2008, table 1.2.6).

## Rainfall-Monitoring Program

Climate change may affect the Hawaiian Islands in several ways. Shifts in rainfall patterns, intensity, and recurrence intervals of extreme rainfall events and droughts have the potential to affect almost every social and economic system in the State. Such climatological changes can also alter the unique biodiversity of Hawai‘i’s ecosystems (Leong and others, 2014). Despite climate change being a primary concern, the rainfall-monitoring program, which was developed in collaboration with WRRC, does not make a clear division between a climate-response network and a water-management network. Rainfall data from both networks are used for assessing a variety of water-resource issues. For example, a rain gage with a long period of record is needed for addressing climate-change effects; however, the same rain gage is also needed for developing gridded rainfall datasets used for estimating water availability (Frazier and others, 2016; Longman and others, 2019). Therefore, the rainfall-monitoring program was developed to address the limitations of the current (2018) program related to insufficient spatial coverage, spatial distribution, and number of rain gages with long periods of record.

## Identifying Monitoring Needs

About two thirds of the land area and rainfall priority areas (described below) of the six major Hawaiian Islands have limited or no rainfall data (table 1). Over half of the rain gages in the current program have a period of record less than the WMO minimum guideline of 30 years for use in determining climate statistics (table 2). The development of the rainfall-monitoring program focused on achieving a representative distribution of rain gages across the islands. Preference was given to five rainfall priority areas—areas that are expected to have the greatest socioeconomic or ecological effects because of climate change.

- **Urban areas**—Most people live and work in these areas, making them important to focus on for social and economic effects from climate change. Identifying changes in the intensity and occurrence of extreme rainfall events that lead to runoff from impervious surfaces is critical for designing and maintaining storm drains and roadways that are capable of handling extreme storm events, which helps keep people and property safe (Paixao and others, 2011). Urban areas were determined as those areas designated as "Urban Land Use District" within the Hawaiʻi State Land Use District Boundaries (State of Hawaiʻi, 2013) geographic information systems (GIS) dataset.

- **Agricultural lands**—Agricultural lands are critical for food production. Shifts in rainfall patterns and changes in recurrence intervals of drought conditions will affect agricultural operations and the allocation of limited surface-water resources (Hatfield and others, 2014). Agricultural lands were determined by combining the "Important Agricultural Lands" (State of Hawaiʻi, 2019b) GIS dataset with the 2015 Hawaiʻi Statewide Agricultural Land Use Baseline (Melrose and others, 2016) dataset with pasture lands removed.

- **High-rainfall areas**—These areas receive at least 118 inches (3,000 mm) of rain annually and are considered important to aquifer recharge. Many important native ecosystems are found in these high-rainfall areas and, because large parts of these areas are remote, few rain gages have been maintained. The limited data have a direct effect on the level of uncertainty of recharge calculations. High-rainfall areas were classified by using the 2013 Rainfall Atlas of Hawaiʻi (Giambelluca and others, 2013) gridded mean annual rainfall GIS dataset. The 118-inch (3,000 mm) threshold was chosen as a conservative value based on plant-moisture zone definitions of wet areas in Hawaiʻi (Price, 2004).

- **High-rainfall gradient areas**—These geographic areas have a rate of change in annual rainfall of 32 inches per mile (500 mm per km) or greater. These areas are sensitive to shifts in rainfall patterns and would benefit from a high density of rain gages for accuracy in determining climatological effects from climate change. A GIS software tool was used to calculate the maximum rate of change between pixel values for the 2013 Rainfall Atlas of Hawaiʻi (Giambelluca and others, 2013) gridded mean annual rainfall GIS dataset. A distinct contrast in the maximum rate of change values was detected at the 32 inches per mile gradient. Therefore, this gradient was selected as the threshold for determining the high-rainfall gradient areas.

- **Trade-wind inversion band areas**—The orographic effect on the moisture-laden trade winds is vertically limited to a mean altitude of about 7,200 ft by the TWI (Giambelluca and Nullet, 1991). The TWI limits the vertical development of clouds and is present about 82 percent of the time; creating dramatic rainfall gradients on the highest mountains of Haleakalā, Mauna Kea, and Mauna Loa (Longman and others, 2015). The base altitude of the TWI layer is susceptible to climate change (Giambelluca and Nullet, 1991), owing to a variety of climatic and physical properties (Cao and others, 2007). In order to capture the spatial and temporal variations of the TWI layer, an altitude range of 5,900–8,500 ft (1,800–2,600 m) was selected from the elevation contours (100-foot contours; State of Hawaiʻi, 1997) GIS dataset for Maui and Hawaiʻi island using GIS software.

## Selection Method

The goal of the rainfall-monitoring program is to address the low rain-gage density and limited distribution by reactivating selected discontinued rain gages and installing new rain gages in priority areas that fill gaps in the current program's rain-gage coverage. Hawaiʻi historically had a high density of rain gages, and although many were discontinued, their locations are known and associated datasets are available. By reactivating some of the discontinued rain gages that have long periods of record, the monitoring program will efficiently take advantage of existing data that are useful for characterizing rainfall.

A dataset of active and discontinued rain gages (Longman and others, 2018) was used to assess coverage of the current program and to determine which discontinued rain gages should be reactivated. A 9.65 $mi^2$ (25 $km^2$) circular buffer zone was created around each active rain gage to represent the WMO-recommended minimum rain-gage density for small islands. Overlapping buffer zones were merged into one GIS layer, which eliminates any overlap. The active rain-gage buffer zone layer exposed areas with inadequate rainfall monitoring coverage and were used to determine percentage of land area and rainfall priority areas covered. Discontinued rain gages with a period of record 30 years or longer (long-term record) that mapped within priority areas lacking coverage were selected for the monitoring program. If no previous rain

**Table 1.** Gage density and effective coverage area of rainfall-monitoring program for Hawai‘i using the World Meteorological Organization rain-gage density standard of one gage per 9.65 square miles ($mi^2$; 25 $km^2$).

[GIS, geographic information system; $mi^2$, square miles]

| Island | Area of island[1], in $mi^2$ | Priority areas, in $mi^2$ | Number of gages | | Gage density, in $mi^2$ per gage | | Effective coverage, in percent of land area | | Effective coverage, in percent of priority area | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Active | Additional[2] | Active | Program[3] | Active | Program[3] | Active | Program[3] |
| Kaua‘i | 554.7 | 105.3 | 50 | 12 | 11.1 | 8.9 | 48.6 | 64.7 | 58.9 | 72.2 |
| O‘ahu | 598.6 | 206.8 | 101 | 10 | 5.9 | 5.4 | 68.9 | 80.2 | 70.0 | 78.3 |
| Moloka‘i | 260.7 | 9.2 | 11 | 15 | 23.7 | 10.0 | 27.1 | 63.9 | 47.3 | 90.2 |
| Lāna‘i | 141.1 | 4.8 | 3 | 8 | 47.0 | 12.8 | 16.4 | 55.7 | 35.1 | 60.7 |
| Maui | 728.8 | 107.5 | 85 | 27 | 8.6 | 6.5 | 49.5 | 70.5 | 45.5 | 65.4 |
| Hawai‘i | 4,039.4 | 1,737.9 | 131 | 101 | 30.8 | 17.4 | 22.6 | 43.9 | 27.7 | 58.6 |
| Statewide | 6,323.3 | 2,171.5 | 381 | 173 | 16.6 | 11.4 | 32.5 | 53.3 | 34.2 | 61.6 |

[1]Area determined using the Coastline GIS dataset (University of Hawai‘i, 2015) and includes GIS dataset of the 2018 eruption of Kīlauea (Hawaiian Volcano Observatory staff, 2018) on the island of Hawai‘i.

[2]Additional gages represent rain gages selected to supplement the current (2018) rainfall-monitoring program.

[3]Effective coverage area of the proposed rainfall-monitoring program also includes coverage of active rain gages. Overlapping areas were merged together so no area was counted twice.

**Table 2.** Distribution of rain gages by length of record for the rainfall-monitoring program for Hawai‘i.

| Island | Gage status[1] | Total number of rain gages | Number of rain gages with indicated length of record | | | |
|---|---|---|---|---|---|---|
| | | | Less than 30 years[2] | 30–49 years | 50–99 years | 100 years or more |
| Kaua‘i | Active | 50 | 23 | 1 | 14 | 12 |
| | Additional | 12 | 2 (2) | 2 | 4 | 2 |
| O‘ahu | Active | 101 | 45 | 17 | 28 | 11 |
| | Additional | 10 | 2 | 1 | 6 | 1 |
| Moloka‘i | Active | 11 | 6 | 0 | 5 | 0 |
| | Additional | 15 | 5 (3) | 3 | 4 | 0 |
| Lāna‘i | Active | 3 | 2 | 0 | 1 | 0 |
| | Additional | 8 | (1) | 2 | 5 | 0 |
| Maui | Active | 85 | 48 | 5 | 13 | 19 |
| | Additional | 27 | 7 (5) | 6 | 8 | 1 |
| Hawai‘i | Active | 131 | 92 | 9 | 14 | 16 |
| | Additional | 101 | 12 (50) | 13 | 23 | 3 |
| Statewide | Active | 381 | 216 | 32 | 75 | 58 |
| | Additional | 173 | 89 | 27 | 50 | 7 |

[1]Additional gages represent rain gages selected to supplement the current (2018) rainfall-monitoring program.

[2]Number in parentheses represents number of new rain gages with no historical data.

gage with a period of record 30 years or longer existed within a priority area lacking coverage, discontinued gages with less than 30 years of record (short-term record) were selected for inclusion in the monitoring program. During this selection process, preference was given to selecting rain gages with the longest period of record for the area in question. If no previous rain gage existed, new rain gages were considered for installation in priority areas within the inadequate-coverage area (table 3).

A total of 173 rain gages have been selected as additional gages needed to address gaps in the current program‘s coverage. Eighty-four discontinued rain gages with a period of record 30 years or greater have been selected for reactivation, 69 of which address gaps in coverage of priority areas. The

**Table 3.** Additional rain gages identified as a need in the rainfall-monitoring program for Hawai‘i.

[BWS, unknown; Cou, course; Dm, Del Monte; Hq, headquarters; Hwy, highway; Int, intake; Landg, landing; Lee, leeward; Molo, Moloka‘i; N, north; NE, northeast; Pow, powerplant; Powerhse, powerhouse; Pt, point; PTA, Pōhakuloa Training Area; Rd, road; Res, reservoir; SE, southeast; SKN, State Key Number; Stn, station; Sug, sugar; SW, southwest; Trib, tributary; Trl, trail; W, west; --, does not exist]

| Island | SKN | Name[1] | Latitude[2] | Longitude[2] | Original Observer | Period of record, in years | Altitude, in feet | Altitude, in meters |
|---|---|---|---|---|---|---|---|---|
| Kaua‘i | 943 | Waiawa | 21.972 | −159.721 | Kekaha Sugar Company | 106 | 10 | 3 |
| Kaua‘i | 1086 | Wainiha Pow Int | 22.148 | −159.567 | McBryde Sugar Company | 101 | 781 | 238 |
| Kaua‘i | 1112 | Kealia | 22.100 | −159.306 | Līhu‘e Plantation | 87 | 18 | 5 |
| Kaua‘i | 1065 | Wailua Kai | 22.037 | −159.341 | Līhu‘e Plantation | 76 | 31 | 10 |
| Kaua‘i | 1102 | Field Makee 2b | 22.123 | −159.351 | Līhu‘e Plantation | 70 | 466 | 142 |
| Kaua‘i | 1052 | Waiahi Upper | 22.020 | −159.464 | Līhu‘e Plantation | 59 | 789 | 241 |
| Kaua‘i | 990.3 | Olokole | 22.034 | −159.552 | Hawaiian Sugar Company | 37 | 1,310 | 399 |
| Kaua‘i | 990.2 | H-M Divide | 22.005 | −159.517 | Hawaiian Sugar Company | 31 | 1,718 | 524 |
| Kaua‘i | 1053.1 | Summit Camp | 22.102 | −159.446 | Kaua‘i Electric | 17 | 1,930 | 588 |
| Kaua‘i | 952.1 | Powerhse Camp 9 | 21.990 | −159.621 | Hawaiian Sugar Company | 13 | 845 | 258 |
| Kaua‘i | -- | Powerline Road | 22.134 | −159.444 | -- | 0 | 1,565 | 477 |
| Kaua‘i | -- | Wainiha River | 22.110 | −159.532 | -- | 0 | 1,620 | 494 |
| O‘ahu | 847 | Waialua | 21.574 | −158.121 | Waialua Agricultural Company/Hydronet | 102 | 23 | 7 |
| O‘ahu | 836 | Waiawa | 21.458 | −157.924 | O‘ahu Sugar Company | 91 | 815 | 249 |
| O‘ahu | 727 | Pump 10 | 21.335 | −158.107 | ‘Ewa Plantation Company | 72 | 30 | 9 |
| O‘ahu | 881 | Helemano Intake | 21.538 | −157.991 | Waialua Agricultural Company | 61 | 1,304 | 398 |
| O‘ahu | 806 | Kunia Dm | 21.457 | −158.059 | Del Monte | 57 | 842 | 257 |
| O‘ahu | 865 | Poamoho | 21.516 | −158.044 | California Packing Corporation | 57 | 941 | 287 |
| O‘ahu | 880 | Kawai Iki | 21.568 | −157.987 | Waialua Agricultural Company | 51 | 1,237 | 377 |
| O‘ahu | 882 | Wahiawa Mauka | 21.513 | −157.946 | Waialua Agricultural Company | 47 | 1,226 | 374 |
| O‘ahu | 883.2 | Kaipapau | 21.582 | −157.942 | Hawaiian Sugar Planters Association | 13 | 2,363 | 720 |
| O‘ahu | 883.3 | Malaekahana | 21.597 | −157.959 | Hawaiian Sugar Planters Association | 10 | 2,204 | 672 |
| Moloka‘i | 542 | Mapulehu | 21.067 | −156.804 | Hawaiian Sugar Planters Association | 81 | 35 | 11 |
| Moloka‘i | 550 | Kepuhi | 21.188 | −157.246 | Moloka‘i Ranch | 75 | 46 | 14 |
| Moloka‘i | 529 | Field 325 | 21.125 | −157.062 | Del Monte | 57 | 324 | 99 |
| Moloka‘i | 562 | Kipu | 21.163 | −157.021 | Del Monte | 53 | 1,285 | 392 |
| Moloka‘i | 503 | Gauge 22 | 21.115 | −157.252 | Libby, McNeil & Libby Company | 48 | 485 | 148 |
| Moloka‘i | 517 | Gauge 27 | 21.154 | −157.178 | Libby, McNeil & Libby Company | 41 | 787 | 240 |
| Moloka‘i | 544 | Puu Lua Wailau | 21.106 | −156.816 | United States Geological Survey | 37 | 2,826 | 861 |
| Moloka‘i | 519 | Puupili | 21.126 | −157.149 | Moloka‘i Ranch | 29 | 1,256 | 383 |
| Moloka‘i | 541.1 | Pepeopae | 21.117 | −156.901 | United States Geological Survey | 22 | 4,120 | 1,256 |

**Table 3.** Additional rain gages identified as a need in the rainfall-monitoring program for Hawai‘i.—Continued

| Island | SKN | Name[1] | Latitude[2] | Longitude[2] | Original Observer | Period of record, in years | Altitude, in feet | Altitude, in meters |
|---|---|---|---|---|---|---|---|---|
| Moloka‘i | 559.6 | Kepali | 21.163 | −156.981 | Moloka‘i Ranch | 15 | 2,033 | 620 |
| Moloka‘i | 543.1 | Puuhoikaweea | 21.131 | −156.875 | Remote Automatic Weather Stations | 2 | 880 | 268 |
| Moloka‘i | 542.5 | Puu Kahea | 21.133 | −156.779 | Pu‘u O Hoku Ranch | 1 | 2,305 | 703 |
| Moloka‘i | -- | Ridge Station | 21.102 | −156.859 | -- | 0 | 4,565 | 1,392 |
| Moloka‘i | -- | Lee East Molo 2 | 21.086 | −156.911 | -- | 0 | 2,160 | 659 |
| Moloka‘i | -- | Ualapue Mauka | 21.079 | −156.836 | -- | 0 | 1,453 | 443 |
| Lāna‘i | 693 | Koele | 20.837 | −156.917 | Dole | 83 | 1,752 | 534 |
| Lāna‘i | 684 | R-4 (Lanai Hale) | 20.811 | −156.872 | Department of Agriculture | 80 | 3,347 | 1,021 |
| Lāna‘i | 694 | Mahana (R-9) | 20.865 | −156.908 | Dole | 73 | 1,506 | 459 |
| Lāna‘i | 650 | R-8 (Palikoholo) | 20.764 | −156.969 | Kō‘ele Company | 69 | 1,239 | 378 |
| Lāna‘i | 665 | 545 | 20.787 | −156.932 | Dole | 57 | 1,260 | 384 |
| Lāna‘i | 653 | 538 | 20.832 | −156.965 | Dole | 48 | 1,262 | 385 |
| Lāna‘i | 696 | R-5 (Keomoku) | 20.850 | −156.827 | Dole | 36 | 4 | 1 |
| Lāna‘i | -- | North Lanai | 20.893 | −156.959 | -- | 0 | 1,028 | 313 |
| Maui | 396 | Puunene | 20.872 | −156.454 | Hawaiian Commercial & Sugar Company | 115 | 60 | 18 |
| Maui | 475 | Mokupea | 20.975 | −156.619 | Baldwin Packers | 89 | 1,399 | 427 |
| Maui | 330 | Gomi | 20.781 | −156.300 | Haleakalā Ranch | 82 | 3,519 | 1,073 |
| Maui | 252 | Auwahi | 20.620 | −156.329 | ‘Ulupalakua Ranch | 73 | 1,976 | 602 |
| Maui | 354 | Hana | 20.750 | −155.987 | Hāna Ranch | 71 | 122 | 37 |
| Maui | 301 | Ukumehame | 20.803 | −156.587 | Pioneer Mill Company | 70 | 59 | 18 |
| Maui | 341 | Honomanu Gulch | 20.777 | −156.224 | Haleakalā Ranch | 66 | 6,189 | 1,887 |
| Maui | 377 | Olowalu Gulch | 20.841 | −156.594 | Pioneer Mill Company | 60 | 762 | 232 |
| Maui | 315 | Pulehu F406 | 20.823 | −156.406 | Hawaiian Commercial & Sugar Company | 57 | 466 | 142 |
| Maui | 481 | Nakalalua | 20.916 | −156.592 | Maui Land & Pineapple Company | 48 | 4,491 | 1,369 |
| Maui | 259.2 | Panileihulu | 20.675 | −156.136 | Kaupō Ranch | 45 | 3,570 | 1,088 |
| Maui | 264 | Waihou | 20.666 | −156.367 | ‘Ulupalakua Ranch | 41 | 3,591 | 1,095 |
| Maui | 259.4 | Central Crater | 20.722 | −156.199 | Haleakalā National Park | 39 | 7,322 | 2,232 |
| Maui | 259.5 | Holua Cabin | 20.742 | −156.218 | Haleakalā National Park | 35 | 6,916 | 2,108 |
| Maui | 260.2 | Keawakapu Beach | 20.695 | −156.444 | Al Corell | 31 | 20 | 6 |
| Maui | 387.2 | Iao Needle | 20.880 | −156.547 | United States Army Corps of Engineers | 28 | 1,250 | 381 |
| Maui | 259 | Kaupo Ranch Hq | 20.647 | −156.136 | Kaupō Ranch | 25 | 935 | 285 |
| Maui | 256.1 | Puu Kao | 20.667 | −156.219 | Haleakalā Ranch | 22 | 3,710 | 1,131 |
| Maui | 351 | Kuhiwa Gulch | 20.777 | −156.111 | East Maui Irrigation Company | 12 | 2,830 | 863 |
| Maui | 254.1 | Manukahi | 20.641 | −156.291 | ‘Ulupalakua Ranch | 11 | 3,245 | 989 |
| Maui | 354.1 | Hana Mauka | 20.752 | −156.024 | Ka‘elekū Sugar Company | 8 | 1,597 | 487 |
| Maui | 350.2 | Nahiku Mauka | 20.793 | −156.097 | W.F. Pogue | 5 | 1,600 | 488 |
| Maui | -- | Waipoli Road | 20.715 | −156.299 | -- | 0 | 6,400 | 1,951 |

**Table 3.** Additional rain gages identified as a need in the rainfall-monitoring program for Hawai‘i.—Continued

| Island | SKN | Name[1] | Latitude[2] | Longitude[2] | Original Observer | Period of record, in years | Altitude, in feet | Altitude, in meters |
|---|---|---|---|---|---|---|---|---|
| Maui | -- | Windward Haleakala | 20.774 | −156.167 | -- | 0 | 4,090 | 1,247 |
| Maui | -- | Windmill | 20.831 | −156.557 | -- | 0 | 3,530 | 1,076 |
| Maui | -- | Naele | 20.793 | −156.335 | -- | 0 | 2,100 | 640 |
| Maui | -- | Kakio | 20.714 | −156.014 | -- | 0 | 930 | 284 |
| Hawai‘i | 88.1 | Kaumana-Hilo Sug | 19.684 | −155.141 | Hilo Sugar Company | 110 | 1,111 | 339 |
| Hawai‘i | 94.1 | Puu Waawaa | 19.773 | −155.842 | Pu‘u Wa‘awa‘a Ranch | 103 | 2,908 | 887 |
| Hawai‘i | 206 | Kukuihaele Landg | 20.125 | −155.559 | Hāmākua Sugar Company | 102 | 306 | 93 |
| Hawai‘i | 222 | Kukaiau-H Mill | 20.027 | −155.342 | Hāmākua Mill Company | 99 | 909 | 277 |
| Hawai‘i | 137 | Honohina | 19.922 | −155.154 | Pepe‘ekeo Sugar Company | 99 | 241 | 73 |
| Hawai‘i | 199 | Kukuihaele HIC | 20.115 | −155.582 | Honoka‘a Sugar Company | 89 | 989 | 302 |
| Hawai‘i | 90 | Wainaku Makai | 19.739 | −155.091 | Mauna Kea Sugar Company | 85 | 83 | 25 |
| Hawai‘i | 118 | Umikoa | 19.980 | −155.379 | Kūka‘iau Ranch | 82 | 3,447 | 1,051 |
| Hawai‘i | 72 | Hualalai | 19.689 | −155.871 | State Division of Forestry | 78 | 8,195 | 2,498 |
| Hawai‘i | 161 | Puakea | 20.232 | −155.871 | Parker Ranch | 78 | 580 | 177 |
| Hawai‘i | 135 | Hakalau Mauka | 19.884 | −155.166 | Pepe‘ekeo Sugar Company | 74 | 1,158 | 353 |
| Hawai‘i | 17 | Moaula Res | 19.198 | −155.527 | Hawaiian Agricultural Company | 72 | 1,817 | 554 |
| Hawai‘i | 212 | First Gate | 20.049 | −155.514 | Parker Ranch | 71 | 2,567 | 783 |
| Hawai‘i | 182.1 | Awini | 20.169 | −155.712 | Kohala Ditch Company | 68 | 1,773 | 541 |
| Hawai‘i | 181.1 | Honokane | 20.145 | −155.731 | Kohala Ditch Company | 67 | 806 | 246 |
| Hawai‘i | 80 | Kalaieha | 19.701 | −155.462 | Parker Ranch | 64 | 6,705 | 2,044 |
| Hawai‘i | 82 | Puu Oo | 19.724 | −155.386 | W.H. Shipman | 64 | 6,268 | 1,911 |
| Hawai‘i | 114 | Hope A | 19.974 | −155.414 | Kūka‘iau Ranch | 64 | 4,030 | 1,229 |
| Hawai‘i | 117 | Halepiula | 19.929 | −155.391 | Kūka‘iau Ranch | 62 | 5,741 | 1,750 |
| Hawai‘i | 120 | Puu Kihe | 19.895 | −155.392 | Kūka‘iau Ranch | 61 | 7,800 | 2,378 |
| Hawai‘i | 73 | Puu Lehua | 19.565 | −155.806 | Greenwell Estate | 61 | 4,857 | 1,481 |
| Hawai‘i | 124.1 | Keanakolu | 19.915 | −155.336 | Parker Ranch | 60 | 5,288 | 1,612 |
| Hawai‘i | 75 | Ahua Umi | 19.634 | −155.779 | Greenwell Estate | 60 | 5,205 | 1,587 |
| Hawai‘i | 68 | Holualoa Beach | 19.605 | −155.976 | Dillingham Investment Corporation | 60 | 4 | 1 |
| Hawai‘i | 97 | Keamuku | 19.840 | −155.717 | Parker Ranch | 57 | 3,106 | 947 |
| Hawai‘i | 44 | Ohaikea | 19.405 | −155.343 | Hawaiian Ranch Company | 52 | 3,481 | 1,061 |
| Hawai‘i | 37 | Pakao | 19.369 | −155.464 | Kapāpala Ranch | 49 | 5,033 | 1,535 |
| Hawai‘i | 183.2 | East Honokane | 20.107 | −155.711 | Kohala Ditch Company | 46 | 4,240 | 1,293 |
| Hawai‘i | 102.1 | Puu Laau | 19.832 | −155.592 | State Division of Forestry | 45 | 7,476 | 2,279 |
| Hawai‘i | 178.3 | Kalope | 20.075 | −155.764 | Kahuā Ranch | 44 | 3,419 | 1,043 |
| Hawai‘i | 167 | Puuokumau | 20.195 | −155.834 | Kohala Sugar Company | 44 | 1,808 | 551 |
| Hawai‘i | 159 | Mahukona | 20.184 | −155.901 | Māhukona Terminals Ltd. | 43 | 19 | 6 |

**Table 3.** Additional rain gages identified as a need in the rainfall-monitoring program for Hawai‘i.—Continued

| Island | SKN | Name[1] | Latitude[2] | Longitude[2] | Original Observer | Period of record, in years | Altitude, in feet | Altitude, in meters |
|---|---|---|---|---|---|---|---|---|
| Hawai‘i | 58 | Ainahou | 19.344 | −155.229 | W.H. Shipman | 41 | 3,026 | 923 |
| Hawai‘i | 107 | Pohaula | 19.750 | −155.527 | State Division of Forestry | 40 | 6,511 | 1,985 |
| Hawai‘i | 105 | Kemole 2-P Ranch | 19.932 | −155.532 | Parker Ranch | 39 | 4,767 | 1,453 |
| Hawai‘i | 70.1 | Halepiula Shed | 19.732 | −155.857 | Pu‘u Wa‘awa‘a Ranch | 36 | 4,463 | 1,361 |
| Hawai‘i | 13 | Waiubata | 19.096 | −155.567 | Hutchinson Sugar Plantation Company | 36 | 1,328 | 405 |
| Hawai‘i | 95.1 | Puako | 19.967 | −155.851 | Goto Ichiro | 36 | 2 | 1 |
| Hawai‘i | 3 | South Pt Corral | 18.947 | −155.680 | Parker Ranch | 33 | 400 | 122 |
| Hawai‘i | 178.2 | Twin Reservoir | 20.184 | −155.787 | Kohala Ditch Company | 28 | 1,924 | 587 |
| Hawai‘i | 84 | Saddle Road | 19.694 | −155.201 | BWS | 25 | 2,308 | 704 |
| Hawai‘i | 12.13 | Hilea Gulch Trib | 19.172 | −155.591 | United States Geological Survey | 24 | 2,246 | 685 |
| Hawai‘i | 43.2 | Pahua Mimi | 19.415 | −155.416 | Kapāpala Ranch | 22 | 5,165 | 1,575 |
| Hawai‘i | 134 | Makahanaloa 2 | 19.817 | −155.192 | State Division of Forestry | 19 | 2,685 | 819 |
| Hawai‘i | 51.9 | Volcano Golf Cou | 19.481 | −155.267 | Wriston Arthur | 17 | 4,198 | 1,280 |
| Hawai‘i | 83.1 | Wailuku River | 19.719 | −155.266 | United States Geological Survey | 15 | 3,621 | 1,104 |
| Hawai‘i | 79.1 | Upper Waiakea | 19.572 | −155.196 | State Division of Forestry | 15 | 2,910 | 887 |
| Hawai‘i | 74.4 | Monohaa | 19.549 | −155.856 | Wall Ranch | 14 | 4,002 | 1,220 |
| Hawai‘i | 30 | Komakawai | 19.399 | −155.772 | McCandless Ranch | 13 | 6,150 | 1,875 |
| Hawai‘i | 192.4 | Holoholuku 1 | 19.974 | −155.636 | Parker Ranch | 7 | 2,938 | 896 |
| Hawai‘i | 37.1 | Mauna Anu | 19.339 | −155.532 | Kapāpala Ranch | 6 | 7,108 | 2,167 |
| Hawai‘i | -- | Ainapo | 19.391 | −155.516 | -- | 0 | 8,127 | 2,478 |
| Hawai‘i | -- | Mauna Loa NE | 19.468 | −155.452 | -- | 0 | 8,121 | 2,476 |
| Hawai‘i | -- | Keauhou 2 | 19.501 | −155.706 | -- | 0 | 8,116 | 2,474 |
| Hawai‘i | -- | Honokua | 19.328 | −155.748 | -- | 0 | 7,555 | 2,303 |
| Hawai‘i | -- | Mauna Loa SE | 19.267 | −155.692 | -- | 0 | 7,551 | 2,302 |
| Hawai‘i | -- | Hilo Kona Rd PTA | 19.627 | −155.540 | -- | 0 | 7,427 | 2,264 |
| Hawai‘i | -- | Hilo Kona Hwy | 19.622 | −155.598 | -- | 0 | 7,424 | 2,264 |
| Hawai‘i | -- | Upper Mauna Loa Lookout | 19.507 | −155.399 | -- | 0 | 7,394 | 2,254 |
| Hawai‘i | -- | Mauna Loa SW | 19.268 | −155.746 | -- | 0 | 7,367 | 2,246 |
| Hawai‘i | -- | Waloala | 19.314 | −155.571 | -- | 0 | 7,362 | 2,244 |
| Hawai‘i | -- | Hilo Kona Rd | 19.639 | −155.476 | -- | 0 | 6,985 | 2,130 |
| Hawai‘i | -- | Hilo Kona Hwy W | 19.609 | −155.667 | -- | 0 | 6,975 | 2,127 |
| Hawai‘i | -- | Kulani | 19.595 | −155.399 | -- | 0 | 6,900 | 2,104 |
| Hawai‘i | -- | Infantry Rd | 19.724 | −155.496 | -- | 0 | 6,829 | 2,082 |
| Hawai‘i | -- | Hualalai SE | 19.678 | −155.816 | -- | 0 | 6,592 | 2,010 |
| Hawai‘i | -- | South Kemole | 19.884 | −155.545 | -- | 0 | 6,482 | 1,976 |
| Hawai‘i | -- | Upper Honalo 2 | 19.551 | −155.738 | -- | 0 | 6,322 | 1,928 |
| Hawai‘i | -- | PTA W | 19.668 | −155.622 | -- | 0 | 6,232 | 1,900 |
| Hawai‘i | -- | Puu Oo Horse Trl | 19.571 | −155.351 | -- | 0 | 6,226 | 1,898 |

**Table 3.** Additional rain gages identified as a need in the rainfall-monitoring program for Hawaiʻi.—Continued

| Island | SKN | Name[1] | Latitude[2] | Longitude[2] | Original Observer | Period of record, in years | Altitude, in feet | Altitude, in meters |
|---|---|---|---|---|---|---|---|---|
| Hawaiʻi | -- | Upper Kau | 19.212 | −155.685 | -- | 0 | 6,198 | 1,890 |
| Hawaiʻi | -- | Saddle Rd Stn 21 | 19.657 | −155.392 | -- | 0 | 5,919 | 1,805 |
| Hawaiʻi | -- | Kiloa 1 | 19.502 | −155.774 | -- | 0 | 5,776 | 1,761 |
| Hawaiʻi | -- | Keokea | 19.443 | −155.796 | -- | 0 | 5,240 | 1,598 |
| Hawaiʻi | -- | Waiaama | 19.740 | −155.332 | -- | 0 | 5,204 | 1,587 |
| Hawaiʻi | -- | Kipahoehoe | 19.270 | −155.811 | -- | 0 | 5,069 | 1,545 |
| Hawaiʻi | -- | Hanaipoe Mana | 19.953 | −155.479 | -- | 0 | 4,946 | 1,508 |
| Hawaiʻi | -- | Honolii | 19.797 | −155.259 | -- | 0 | 4,216 | 1,285 |
| Hawaiʻi | -- | Kaloko | 19.701 | −155.926 | -- | 0 | 4,201 | 1,281 |
| Hawaiʻi | -- | Stainback Waiakea | 19.589 | −155.259 | -- | 0 | 3,950 | 1,204 |
| Hawaiʻi | -- | Stainback Olaa | 19.540 | −155.238 | -- | 0 | 3,847 | 1,173 |
| Hawaiʻi | -- | Upper Waiakea 2 | 19.640 | −155.256 | -- | 0 | 3,640 | 1,110 |
| Hawaiʻi | -- | Kona Hema | 19.218 | −155.830 | -- | 0 | 3,610 | 1,101 |
| Hawaiʻi | -- | Umauma | 19.866 | −155.239 | -- | 0 | 3,549 | 1,082 |
| Hawaiʻi | -- | Punono | 20.011 | −155.497 | -- | 0 | 3,330 | 1,015 |
| Hawaiʻi | -- | Volcano 62 | 19.402 | −155.169 | -- | 0 | 2,913 | 888 |
| Hawaiʻi | -- | Kaiwiki Mauka | 19.763 | −155.203 | -- | 0 | 2,854 | 870 |
| Hawaiʻi | -- | Kaimu | 20.132 | −155.661 | -- | 0 | 2,700 | 823 |
| Hawaiʻi | -- | Fern Forest | 19.448 | −155.124 | -- | 0 | 2,300 | 701 |
| Hawaiʻi | -- | Flume Rd 2 | 19.636 | −155.182 | -- | 0 | 2,217 | 676 |
| Hawaiʻi | -- | Pohakupuka | 19.918 | −155.217 | -- | 0 | 2,050 | 625 |
| Hawaiʻi | -- | Apele Forest | 19.427 | −155.065 | -- | 0 | 1,986 | 606 |
| Hawaiʻi | -- | N Kulani | 19.600 | −155.144 | -- | 0 | 1,764 | 538 |
| Hawaiʻi | -- | Waiula | 20.019 | −155.754 | -- | 0 | 1,600 | 488 |
| Hawaiʻi | -- | Waiea | 19.360 | −155.866 | -- | 0 | 1,508 | 460 |
| Hawaiʻi | -- | Upper Puna | 19.400 | −155.012 | -- | 0 | 1,356 | 413 |
| Hawaiʻi | -- | Upper Pahoa 2 | 19.464 | −154.987 | -- | 0 | 1,177 | 359 |
| Hawaiʻi | -- | Kea 11 | 19.576 | −155.044 | -- | 0 | 705 | 215 |
| Hawaiʻi | -- | Puu Oo Crater | 19.351 | −155.117 | -- | 0 | 211 | 694 |
| Hawaiʻi | -- | Kiele | 19.606 | −154.979 | -- | 0 | 115 | 35 |
| Hawaiʻi | -- | Kapoho Coast | 19.693 | −155.009 | -- | 0 | 37 | 11 |

[1]Original station names used which do not include Hawaiian diacritical marks.

[2]Latitude and longitude coordinates in North American Datum of 1983.

other 15 rain gages with long-term record are located in areas needed to address the limited spatial distribution. Twenty-eight discontinued rain gages with periods of record less than 30 years have been selected for reactivation, all of which will address the lack of coverage in rainfall priority areas and improve spatial distribution. An additional 61 new rain gages are selected to address the lack of coverage of priority areas and overall distribution. A 9.65 $mi^2$ (25 $km^2$) circular buffer zone was created around each rain gage in the monitoring program. Overlapping buffer zones of the rain gages were merged, eliminating any overlap. The effective coverage area of the additional rain gages was then merged with the active rain gage effective coverage areas. Overlapping areas in combined effective coverage areas were eliminated to avoid counting them twice and then using them to calculate percentage of land area and rainfall priority area covered if all rain gages

were installed. Accessibility to the locations of the additional rain gages may have an effect on the order in which rain gages can be reactivated. This assessment should be done as part of implementing the rainfall-monitoring program.

### Kaua‘i

Kaua‘i has 50 active rain gages that provide an effective coverage area of almost half of the land area and about 60 percent of total priority areas (table 1). Many of these rain gages are located along the northern, eastern, and southern coastal areas of the island (fig. 5). Most of the interior of the island has high rainfall and a high-rainfall gradient with very limited rain-gage coverage (tables 4, 5). The monitoring program includes reactivation of eight rain gages with long-term record, two rain gages with short-term record, and installation of two new rain gages (fig. 5 and table 2). The addition of these 12 rain gages would increase island-wide coverage by more than 15 percent of land area, more than 10 percent of priority areas, and bring the average island-wide gage density to within the WMO-recommended minimum gage density (table 1).

### O‘ahu

O‘ahu has the highest density of rain gages of any island in the State with 101 active rain gages covering almost 70 percent of the island and 70 percent of total priority areas (table 1). Many of these rain gages are located in urban areas in the southern and eastern parts of the island (fig. 6). Although the island has a high density of rain gages, coverage is limited in the island’s agricultural, high-rainfall, and high-rainfall gradient areas in the eastern part of the island. The monitoring program includes reactivation of eight rain gages with long-term record and two rain gages with short-term record. The addition of these 10 rain gages would increase island-wide coverage by more than 10 percent of land area and increase priority-area coverage by about 10 percent.

### Moloka‘i

Moloka‘i has 11 active rain gages that provide an effective coverage area of less than one third of the land area and just under half of total priority areas (table 1). None of these rain gages are located within high-rainfall or high-rainfall gradient areas (table 4). Furthermore, the eastern half of East Moloka‘i volcano does not have any active rain gages (fig. 7). The monitoring program includes reactivating seven rain gages with long-term record and five rain gages with short-term record and installing three new rain gages. The one rain gage covering a priority area in the northwest part of the island has a period of record of 4 years; therefore, the reactivation of a rain gage with a period of record of more than 70 years has been selected as a need for the area. The addition of these 15 rain gages would increase island-wide coverage by more than 35 percent of land area, increase priority-area coverage by more than 40 percent, and dramatically improve the spatial coverage and distribution.

### Lāna‘i

Lāna‘i has three active rain gages, making it the least covered island of the six major islands with less than 20 percent of land area and approximately 35 percent of total priority areas covered (table 1). The island is also the smallest of the six major islands and does not have any high-rainfall, high-rainfall gradient, or TWI-band priority areas. Despite the absence of these priority areas, seven rain gages with long-term record and one new rain gage are selected for inclusion in the monitoring program (fig. 8). The only town on the island, Lāna‘i City, has 1 active rain gage with a period of record less than 30 years; therefore, the reactivation of a rain gage with a period of record of more than 80 years has been identified as a need for the area. The addition of these 8 rain gages would increase island-wide coverage by about 40 percent of land area, increase priority-area coverage by 25 percent, and provide an appropriate distribution of spatial coverage.

### Maui

Maui has 85 active rain gages that provide an effective coverage area of about half of the land area and less than half of total priority areas (table 1). Owing to the cessation of sugarcane cultivation and the associated rain gages in 2016, central Maui has few active gages. The high-rainfall and high-rainfall gradient areas of west Maui also have insufficient coverage along with a large part of east Maui. The monitoring program includes reactivating 15 rain gages with long-term record and 7 rain gages with short-term record and installing 5 new rain gages (fig. 9). The addition of 27 rain gages would increase effective coverage by more than 20 percent of both land area and priority areas and would provide coverage in areas that are critical for monitoring water availability and areas sensitive to climate change. The summit area of Haleakalā has exceptional rain-gage coverage; however, these gages have short periods of record. Therefore, the TWI-band priority area would benefit by reactivating two rain gages with long-term record.

### Hawai‘i

Hawai‘i island has the most active rain gages (131) of the six major islands; however, it has more land area than the other five islands combined, and only about one-fifth of the land area has rain-gage coverage (table 1). The island has the least amount of priority areas covered by rain gages with less than 30 percent coverage (table 1). The monitoring program includes reactivating 39 rain gages with long-term record and 12 rain gages with short-term record and installing 50 new rain gages (fig. 10 and table 2). The addition of these 101 rain gages would increase island-wide coverage by about 20 percent of land area, increase priority-area coverage by about 30 percent, and address the lack of coverage within the TWI-band, high-rainfall, and high-rainfall gradient priority areas.

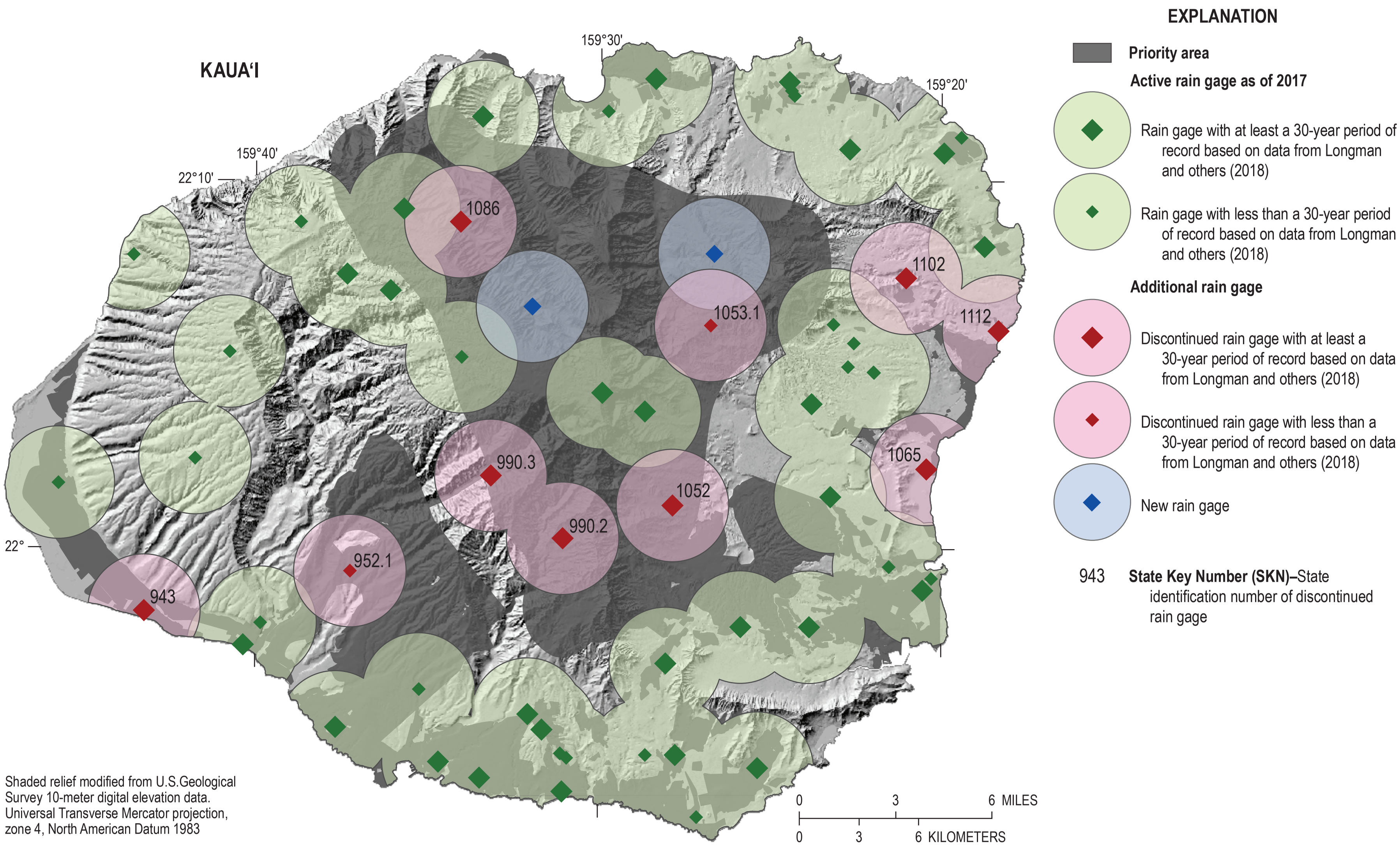



**Figure 5.** Map showing the rain-gage coverage of the rainfall-monitoring program on Kaua‘i, Hawai‘i. Rain gages are shown with a 9.65 square mile (25 square kilometer [$km^2$]) circular area centered around the gage (offshore area not shown). The World Meteorological Organization recommends a rain-gage density of at least one gage per 25 $km^2$ for small islands.

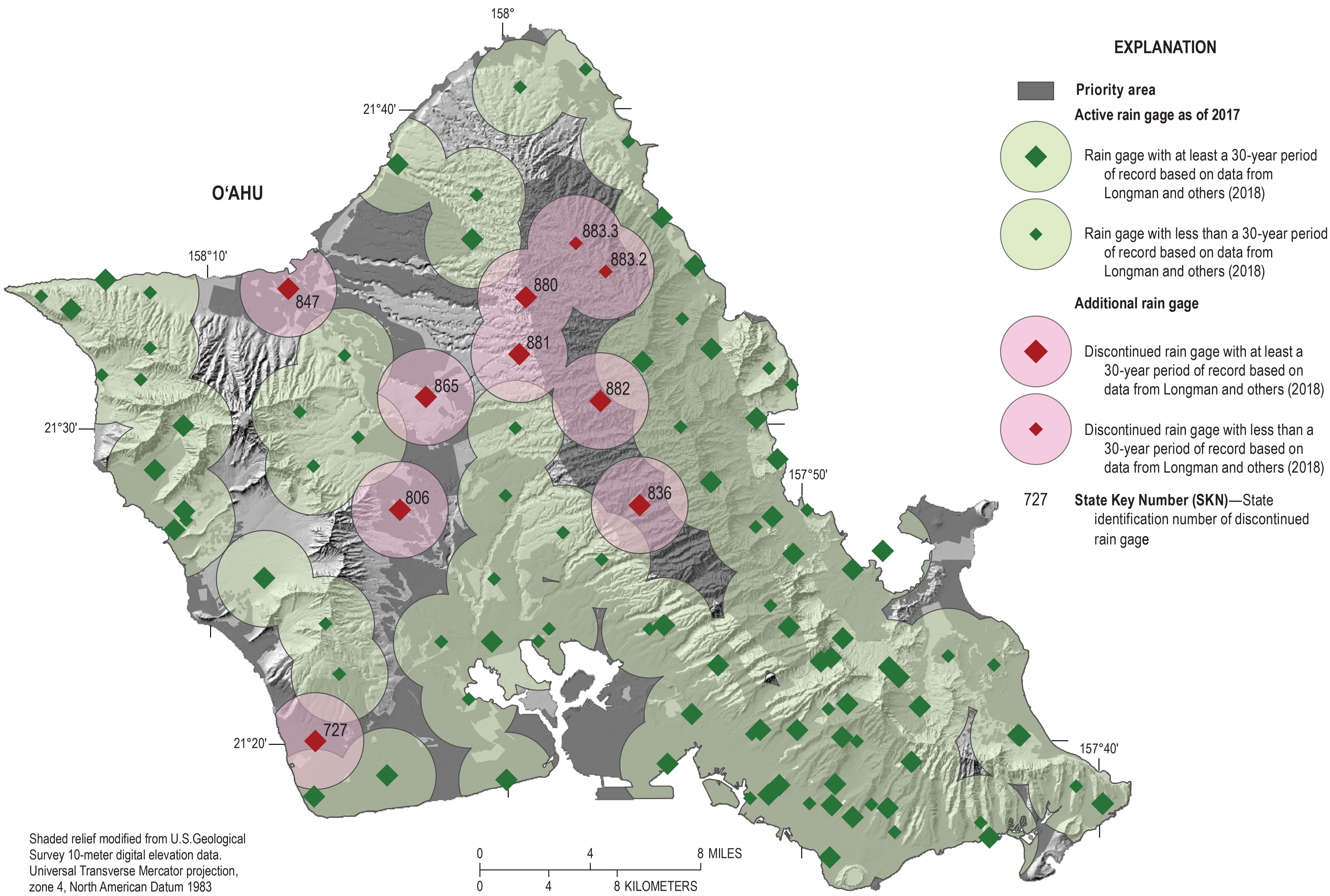



**Figure 6.** Map showing the rain-gage coverage of the rainfall-monitoring program on O‘ahu, Hawai‘i. Rain gages are shown with a 9.65 square mile (25 square kilometer [$km^2$]) circular area centered around the gage (offshore area not shown). The World Meteorological Organization recommends a rain-gage density of at least one gage per 25 $km^2$ for small islands.

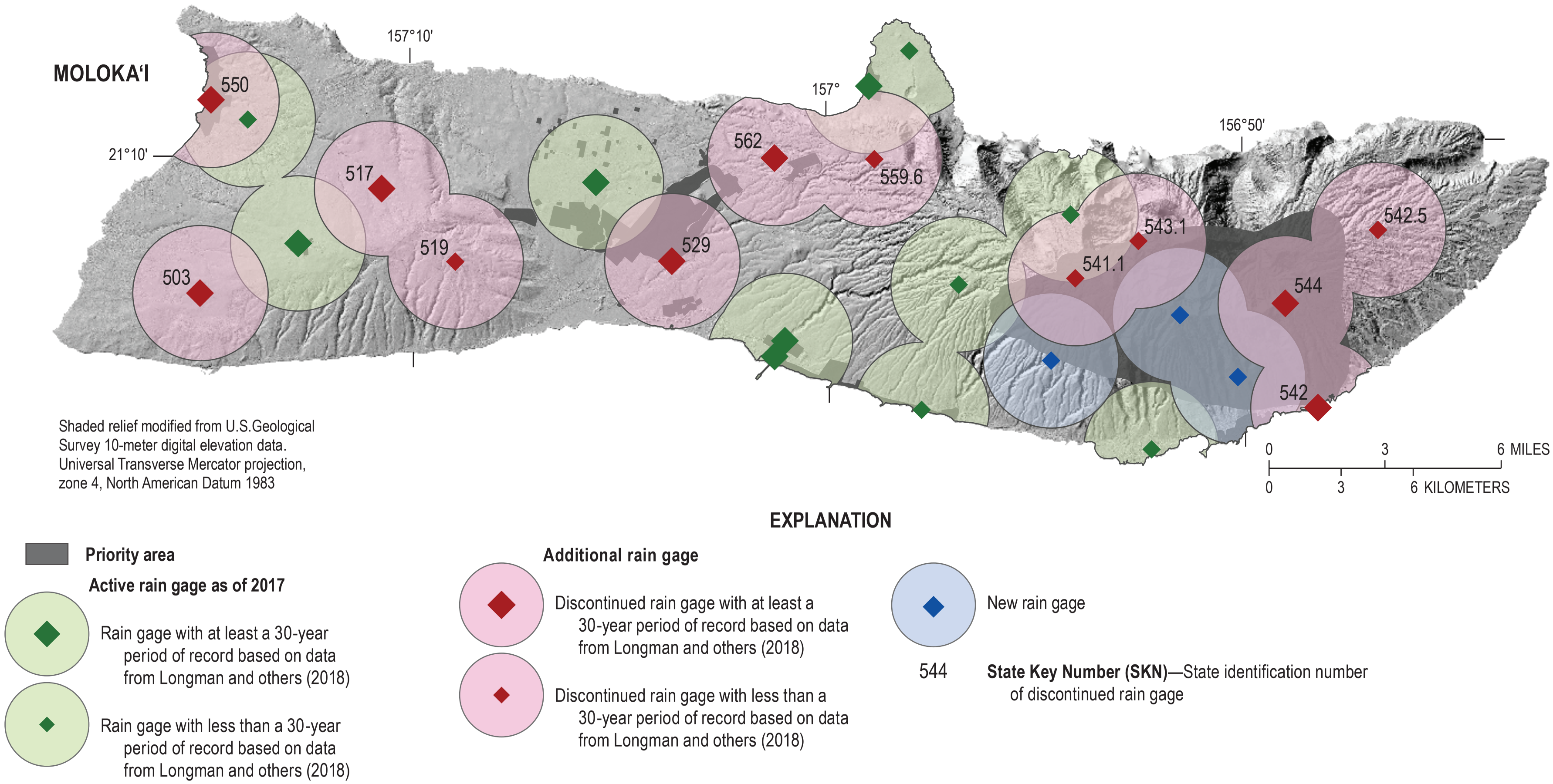



**Figure 7.** Map showing the rain-gage coverage of the rainfall-monitoring program on Moloka‘i, Hawai‘i. Rain gages are shown with a 9.65 square mile (25 square kilometer [$km^2$]) circular area centered around the gage (offshore area not shown). The World Meteorological Organization recommends a rain-gage density of at least one gage per 25 $km^2$ for small islands.

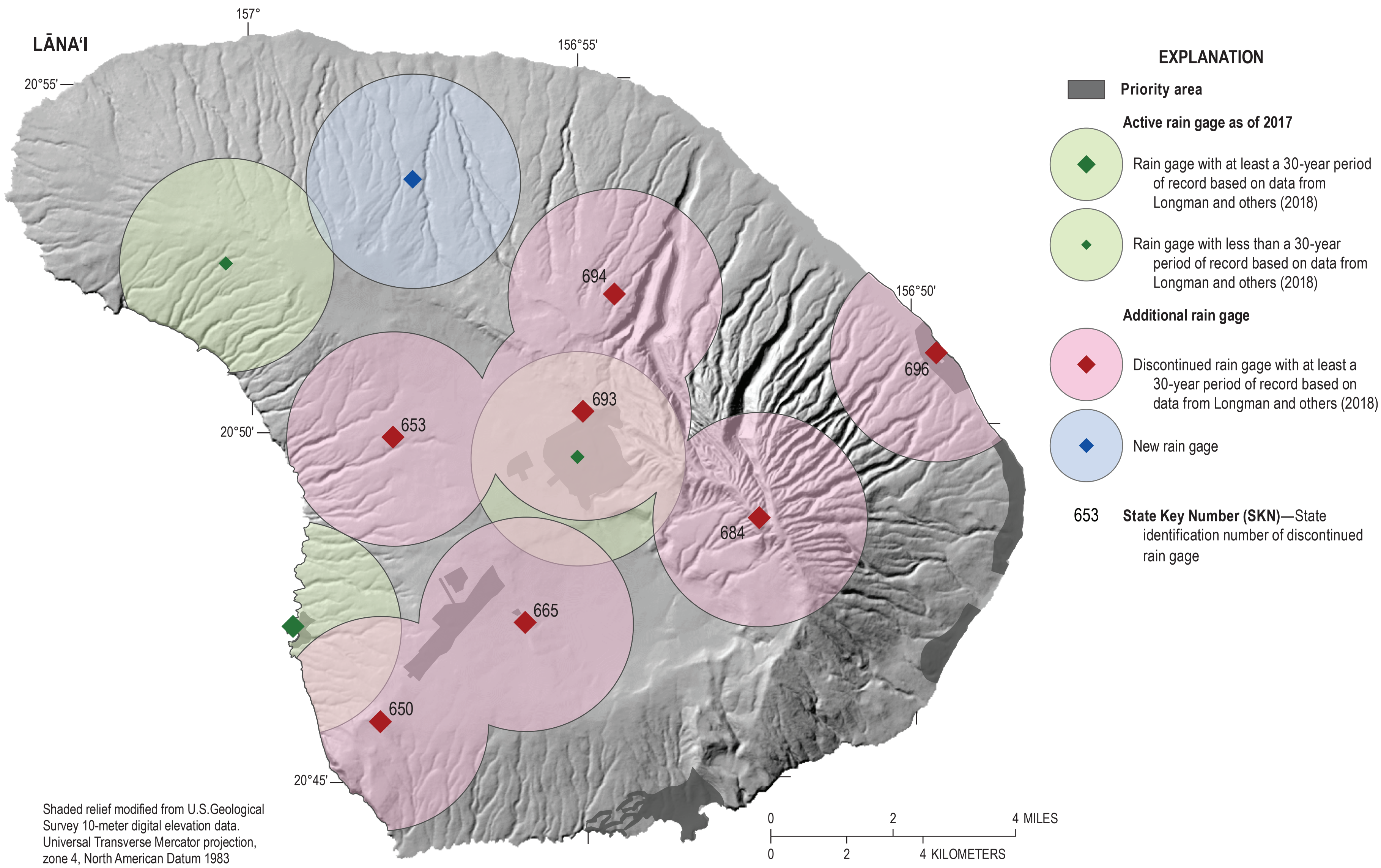



**Figure 8.** Map showing the rain-gage coverage of the rainfall-monitoring program on Lānaʻi, Hawaiʻi. Rain gages are shown with a 9.65 square mile (25 square kilometer [$km^2$]) circular area centered around the gage (offshore area not shown). The World Meteorological Organization recommends a rain-gage density of at least one gage per 25 $km^2$ for small islands.

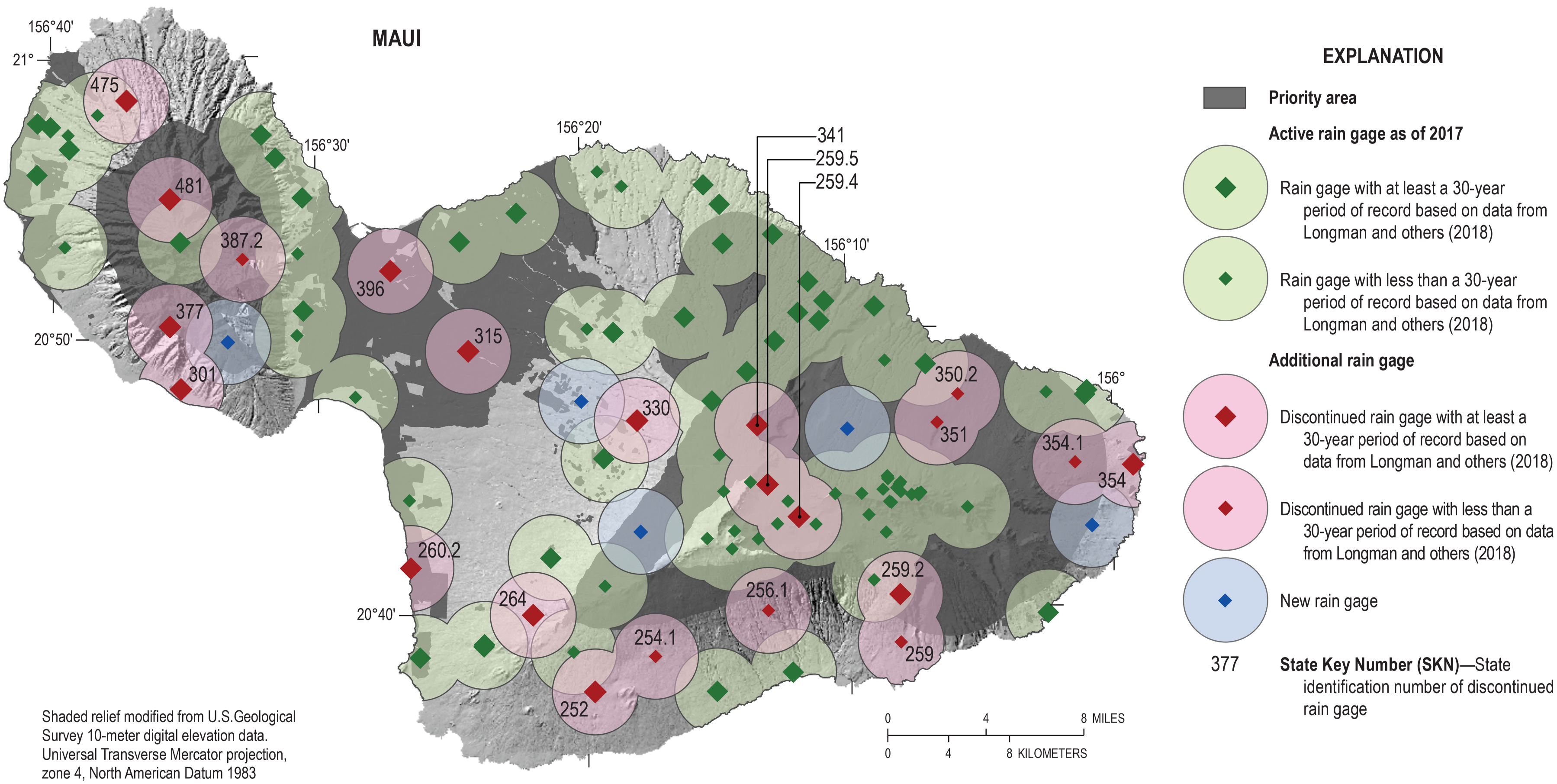



**Figure 9.** Map showing the rain-gage coverage of the rainfall-monitoring program on Maui, Hawai‘i. Rain gages are shown with a 9.65 square mile (25 square kilometer [km$^2$]) circular area centered around the gage (offshore area not shown). The World Meteorological Organization recommends a rain-gage density of at least one gage per 25 km$^2$ for small islands.

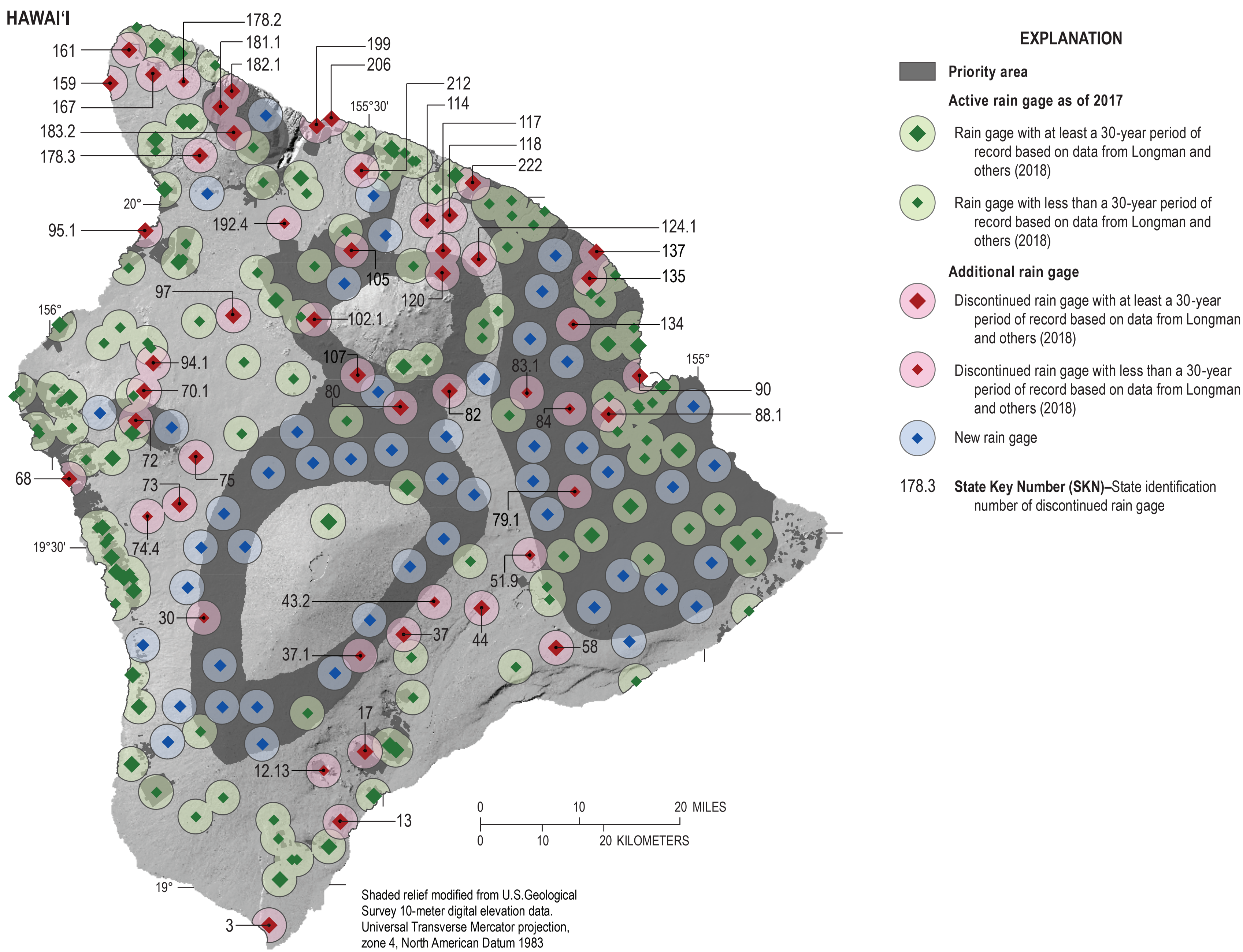



**Figure 10.** Map showing the rain-gage coverage of the rainfall-monitoring program on Hawai'i island, Hawai'i. Rain gages are shown with a 9.65 square mile (25 square kilometer [$km^2$]) circular area centered around the gage (offshore area not shown). The World Meteorological Organization recommends a rain-gage density of at least one gage per 25 $km^2$ for small islands.

**Table 4.** Distribution of rain gages by mean annual rainfall for the rainfall-monitoring program for Hawai‘i.

[--, not applicable]

| Island | Gage status[1] | Total number of rain gages | Number of gages by mean annual rainfall in inches | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Less than 40 | 40–<80 | 80–<118 | 118–<160 | 160–<200 | 200 or more |
| Kaua‘i | Active | 50 | 12 | 25 | 9 | 1 | 1 | 2 |
| | Additional | 12 | 2 | 3 | 0 | 6 | 1 | 0 |
| O‘ahu | Active | 101 | 39 | 40 | 13 | 7 | 0 | 2 |
| | Additional | 10 | 3 | 2 | 1 | 4 | 0 | 0 |
| Moloka‘i | Active | 11 | 8 | 2 | 1 | 0 | 0 | -- |
| | Additional | 15 | 7 | 3 | 1 | 3 | 1 | -- |
| Lāna‘i | Active | 3 | 3 | -- | -- | -- | -- | -- |
| | Additional | 8 | 8 | -- | -- | -- | -- | -- |
| Maui | Active | 85 | 24 | 22 | 8 | 7 | 11 | 13 |
| | Additional | 27 | 10 | 6 | 6 | 1 | 0 | 4 |
| Hawai‘i | Active | 131 | 47 | 36 | 15 | 20 | 9 | 4 |
| | Additional | 101 | 37 | 23 | 11 | 12 | 6 | 12 |
| Statewide | Active | 381 | 133 | 125 | 46 | 35 | 21 | 21 |
| | Additional | 173 | 67 | 37 | 19 | 26 | 8 | 16 |

[1]Additional gages represent rain gages selected to supplement the current (2018) rainfall-monitoring program.

**Table 5.** Distribution of active rain gages by elevation for the rainfall-monitoring program for Hawai‘i.

[--, not applicable]

| Island | Maximum altitude,[1] in feet | Gage status[2] | Number of gages by altitude in feet[3] | | | |
|---|---|---|---|---|---|---|
| | | | 0–1,999 | 2,000–3,999 | 4,000–6,000 | More than 6,000 |
| Kaua‘i | 5,243 | Active | 42 | 5 | 3 | -- |
| | | Additional | 12 | 0 | 0 | -- |
| O‘ahu | 4,003 | Active | 98 | 3 | 0 | -- |
| | | Additional | 8 | 2 | 0 | -- |
| Moloka‘i | 4,961 | Active | 9 | 2 | 0 | -- |
| | | Additional | 9 | 4 | 2 | -- |
| Lāna‘i | 3,366 | Active | 3 | 0 | -- | -- |
| | | Additional | 7 | 1 | -- | -- |
| Maui | 10,023 | Active | 42 | 7 | 5 | 31 |
| | | Additional | 13 | 8 | 2 | 4 |
| Hawai‘i | 13,796 | Active | 82 | 24 | 13 | 12 |
| | | Additional | 28 | 25 | 20 | 28 |
| Statewide | -- | Active | 276 | 41 | 21 | 43 |
| | | Additional | 77 | 40 | 24 | 32 |

[1]Altitude values from State of Hawai‘i (2018d).

[2]Additional gages represent rain gages selected to supplement the current (2018) rainfall-monitoring program.

[3]Rain gage altitude rounded to the nearest whole number.

# Surface Water

Surface-water monitoring is used to characterize discharge at a selected location in a stream, ditch, or spring. Discharge data can be collected on a continuous basis by using data loggers that record gage heights and applying continuous gage-height data to a stage-discharge relation, or discrete basis that measures flow at a specific time by using current meters or acoustic velocity meters. The data-collection location, methods, duration, and frequency depend on the objectives of the monitoring program and desired data quality.

The USGS is the principal source of surface-water information in Hawaiʻi. Hence, this section of the report will describe surface-water information that is collected by the USGS and available in the NWIS database. A detailed account of the historical surface-water monitoring program is included in Fontaine (1996, p. 6–9); therefore, only a brief summary will be included in this report. The USGS cooperative surface-water resource-monitoring program in Hawaiʻi initially (1909) focused on surface-water monitoring with the establishment of 12 continuously recording gages. The initial monitoring program expanded rapidly, and by 1914, 87 continuously recording gages were in operation. Most of these gages were operated to quantify water-supply potential for agricultural irrigation needs. Several of the early gages were discontinued after operating for only a short period because long-term records were deemed unnecessary. The monitoring program continued to expand, although at a more gradual pace, and by 1940 about 143 continuously recording gages were in operation. During most of the 1940s and early 1950s, the size of the monitoring program remained relatively stable. During the mid-1950s, expansion of the monitoring program resumed and by 1966, about 197 continuously recording gages were being operated by the USGS in Hawaiʻi. Since 1966, the size of the monitoring program has declined substantially. Decisions to discontinue operation of streamflow gages were based on several economic and technical reasons. Primarily, streamflow gages were discontinued because original objectives were met, and funding was not available to continue their operation to meet potential future needs.

The current (2018) surface-water monitoring program operated by the USGS in Hawaiʻi, excluding crest-stage stations, consists of 65 continuous-record streamflow-gaging stations, 12 continuous-record low-flow gaging stations (table 6), one continuous-record ditch-flow-gaging station, and 65 partial-record stations (table 7). Eighteen of the partial-record stations on Kauaʻi were established in 2016 as part of a study to understand low flows for streams in southeast Kauaʻi. Eleven continuous-record low-flow gaging stations and 45 partial-record stations were established in late 2018 as part of a study to estimate low-flow characteristics at ungaged basins statewide using regional-regression analysis of low-flow and drainage-basin characteristics at gaged basins. The partial-record stations established as part of the two studies will be discontinued at the conclusion of the studies. The different types of stations are described in “Data-Collection Strategies” within the “Surface Water” section of this report.

## Current Surface-Water Resource Issues

Many of the surface-water resource issues evaluated by Fontaine (1996, p. 3) have continued to guide USGS surface-water resource-monitoring efforts. Input received from the stakeholder workshops indicated that three issues have become increasingly critical in determining the adequacy of the current surface-water resource-monitoring program and the need for additional data collection to supplement the current program. The three key issues are (1) changes in surface-water use, (2) availability of surface-water resources during low-flow conditions, and (3) regulatory developments to effectively allocate instream and off-stream uses of surface water. These issues will be fundamental in reshaping the Hawaiʻi surface-water resource-monitoring program.

### Changes in Surface-Water Use

Surface water in Hawaiʻi was primarily used to support the irrigation needs of large-scale monocrop agriculture, particularly sugarcane plantations, during much of the 1900s. By 1920, more than 50 sugarcane plantations were established and more than 800 million gallons per day of water were regularly diverted from Hawaiian streams (Wilcox, 1996). Substantial changes in surface-water use began in the late-1980s as a result of decreasing plantation agriculture and increasing urbanization. According to Hawaiʻi State Department of Agriculture (State of Hawaiʻi, 2016b, p. 14 and 20), total active cropland in 2015 was less than half of that in 1980. Former plantation lands that were not used for crop cultivation were converted to pastures for cattle operations or transformed to residential developments. In December 2016, closure of Hawaiian Commercial and Sugar Company’s (HC&S) sugarcane plantation in central Maui marked the end of large-scale plantation agriculture. HC&S has established cattle operations for about 4,000 acres of its 36,000-acre plantation and continues to evaluate alternative agricultural uses for the remaining portion of its land (Murar, 2017).

Many of the large engineered diversion systems that were originally built to support the irrigation-water demands of the early plantations remain today, and parts of the systems are currently being maintained by State agencies and private entities to support other agricultural and municipal uses. Some diversion systems continue to transport water within and across drainage basins, altering drainage patterns and ultimately affecting native stream biota and water availability for downstream water users. Former plantation diversion systems are most likely operating at reduced capacities as a result of reduced demand from emerging new agricultural activities (State of Hawaiʻi, 2016b, p. 85) and downsizing of the systems to lower costs in infrastructure maintenance. The diversions typically captured all of the dry-weather flow of streams and stream reaches downstream of the diversion intakes commonly were dry. Currently, about 1,380 stream diversions are registered and permitted statewide; however, the status of only a fraction of these diversions has been field verified (State of Hawaiʻi, 2019c).

**Table 6.** U.S. Geological Survey (USGS) continuous-record gaging stations in Hawaiʻi in operation during water year 2018, with discharges available in the National Water Information System (NWIS) database.

[abv, above; alt, altitude; blw, below; Dtch, ditch; E, East; EB, East Branch; EF, East Fork; ft, feet; HI, Hawaii; Hwy, Highway; intk, intake; LB, Left Branch; LF, low flow; N., North; NF, North Fork; nr, near; P, present (2018); PL, Pipeline; Quar., Quarantine; RB, Right Branch; Rd, Road; Rv, River; Riv, River; SF, South Fork; St., Street; Stn., Station; US, upstream]

| Station ID | Station name[1] | Altitude,[2] in feet | Latitude[3] | Longitude[3] | Aspect | Period of record | Years of record[4] | Flow classification |
|---|---|---|---|---|---|---|---|---|
| Kauaʻi | | | | | | | | |
| 16010000 | Kawaikoi Stream nr Waimea, Kauai, HI | 3,420 | 22.133 | −159.620 | Leeward | 1909–16, 1919–P | 101 | Natural |
| 16019000 | Waialae Str at alt 3,820 ft nr Waimea, Kauai, HI | 3,820 | 22.086 | −159.569 | Leeward | 1920–32, 1952–P | 76 | Natural |
| 16031000 | Waimea River near Waimea, Kauai, HI | 20 | 21.980 | −159.660 | Leeward | 1910–19, 1943–72, 1975–97, 2016–P | 55 | Regulated |
| 16036000 | Makaweli River nr Waimea, Kauai, HI | 20 | 21.971 | −159.646 | Leeward | 1943–P | 75 | Regulated |
| 16049000 | Hanapepe Riv blw Manuahi Str nr Eleele, Kauai, HI | 220 | 21.955 | −159.551 | Leeward | 1917–21, 1926–P | 94 | Regulated |
| 16057900 | Waiahi Str US Upper Powerhouse, Kauai, HI | 820 | 22.023 | −159.465 | Windward | 2015–P (LF only) | 2 | Natural |
| 16060000 | SF Wailua River nr Lihue, Kauai, HI | 240 | 22.037 | −159.380 | Windward | 1912–P | 101 | Regulated |
| 16068000 | EB of NF Wailua River nr Lihue, Kauai, HI | 500 | 22.069 | −159.415 | Windward | 1912–P | 103 | Natural |
| 16071500 | Left Branch Opaekaa Str nr Kapaa, Kauai, HI | 460 | 22.076 | −159.396 | Windward | 1960–P | 58 | Natural |
| 16097500 | Halaulani Str at alt 400 ft nr Kilauea, Kauai, HI | 390 | 22.179 | −159.419 | Windward | 1957–P | 60 | Natural |
| 16103000 | Hanalei River nr Hanalei, Kauai, HI | 60 | 22.180 | −159.466 | Windward | 1912–19, 1963–P | 61 | Natural beginning 1995 |
| 16108000 | Wainiha River nr Hanalei, Kauai, HI | 960 | 22.136 | −159.558 | Windward | 1952–P | 62 | Natural |
| Oʻahu | | | | | | | | |
| 16200000 | NF Kaukonahua Str abv RB, nr Wahiawa, Oahu, HI | 1,150 | 21.516 | −157.945 | Leeward | 1913–53, 1960–P | 95 | Natural |
| 16208000 | SF Kaukonahua Str at E pump, nr Wahiawa, Oahu, HI | 860 | 21.489 | −157.996 | Leeward | 1957–63, 1964–2011, 2013–P | 55 | Natural |
| 16210100 | Wahiawa Ditch at Wahiawa, Oahu, HI | 790 | 21.500 | −158.051 | Leeward | 2012–P | 6 | Regulated |
| 16210200 | Kaukonahua Stream blw Wahiawa Reservoir, Oahu, HI | 760 | 21.500 | −158.051 | Leeward | 2013–P | 4 | Regulated |
| 16210500 | Kaukonahua Str at Waialua, Oahu, HI | 20 | 21.565 | −158.120 | Leeward | 2012–P | 6 | Regulated |
| 16211600 | Makaha Str nr Makaha, Oahu, HI | 940 | 21.501 | −158.180 | Leeward | 1959–P | 58 | Regulated |
| 16212480 | Honouliuli Stream Tributary near Waipahu, Oahu, HI | 630 | 21.402 | −158.067 | Leeward | 2012–P | 6 | Natural |
| 16212490 | Honouliuli Str at H-1 Freeway nr Waipahu, Oahu, HI | 140 | 21.378 | −158.045 | Leeward | 2012–P | 5 | Regulated |

**Table 6.** U.S. Geological Survey (USGS) continuous-record gaging stations in Hawai‘i in operation during water year 2018, with discharges available in the National Water Information System (NWIS) database.—Continued

| Station ID | Station name[1] | Altitude,[2] in feet | Latitude[3] | Longitude[3] | Aspect | Period of record | Years of record[4] | Flow classification |
|---|---|---|---|---|---|---|---|---|
| | | | | O‘ahu—Continued | | | | |
| 16212601 | Waikele Str at Wheeler Field, Oahu, HI | 710 | 21.472 | −158.044 | Leeward | 2007–10, P | 3 | Natural |
| 16213000 | Waikele Str at Waipahu, Oahu, HI | 1 | 21.383 | −158.011 | Leeward | 1951–P | 64 | Regulated |
| 16226200 | N. Halawa Str nr Honolulu, Oahu, HI | 160 | 21.382 | −157.903 | Leeward | 1983–P | 35 | Natural |
| 16226400 | N. Halawa Str nr Quar. Stn. at Halawa, Oahu, HI | 60 | 21.372 | −157.913 | Leeward | 2001–03, 2005–P | 15 | Natural |
| 16227500 | Moanalua Stream nr Kaneohe, Oahu, HI | 690 | 21.388 | −157.849 | Leeward | 1968–78, 2013–P | 14 | Natural |
| 16229000 | Kalihi Str nr Honolulu, Oahu, HI | 460 | 21.363 | −157.844 | Leeward | 1913–P | 104 | Natural |
| 16238000 | Makiki Stream at King St. bridge, Oahu, HI | 10 | 21.297 | −157.837 | Leeward | 2010–P | 7 | Regulated |
| 16238500 | Waihi Stream at Honolulu, Oahu, HI | 290 | 21.328 | −157.801 | Leeward | 1913–21, 1925–83, 2011–P | 71 | Natural beginning 1983 |
| 16240500 | Waiakeakua Str at Honolulu, Oahu, HI | 290 | 21.328 | −157.800 | Leeward | 1913–20, 1925–P | 100 | Natural |
| 16241600 | Manoa Stream at Woodlawn Drive, Oahu, HI | 130 | 21.308 | −157.810 | Leeward | 2011–P | 6 | Natural |
| 16244000 | Pukele Stream near Honolulu, Oahu, HI | 340 | 21.307 | −157.788 | Leeward | 1926–82, 2002–05, 2010–P | 66 | Natural |
| 16247100 | Manoa-Palolo Drainage Canal at Moiliili, Oahu, HI | 5 | 21.286 | −157.818 | Leeward | 1999–P | 18 | Regulated |
| 16249000 | Waimanalo Str at Waimanalo, Oahu, HI | 20 | 21.350 | −157.729 | Windward | 1967–70, 2015–P | 5 | Regulated |
| 16254000 | Makawao Str nr Kailua, Oahu, HI | 100 | 21.360 | −157.762 | Windward | 1912–16, 1958–2006, 2008–P | 58 | Regulated |
| 16264690 | Kawainui Stream near Kailua, Oahu, HI | 160 | 21.393 | −157.774 | Windward | 2016–P | 0 | Regulated |
| 16265000 | Kawa Str at Kaneohe, Oahu, HI | 50 | 21.406 | −157.790 | Windward | 2016–P | 2 | Natural |
| 16274100 | Kaneohe Str blw Kamehameha Hwy, Oahu, HI | 30 | 21.412 | −157.798 | Windward | 2016–P | 2 | Regulated |
| 16275000 | Heeia Stream at Haiku Valley nr Kaneohe, Oahu, HI | 270 | 21.409 | −157.823 | Windward | 1914–19, 1939–77, 1982–P | 78 | Regulated |
| 16283200 | Kahaluu Str nr Ahuimanu, Oahu, HI | 150 | 21.439 | −157.844 | Windward | 1983–P | 35 | Regulated |
| 16284200 | Waihee Str nr Kahaluu, Oahu, HI | 170 | 21.448 | −157.857 | Windward | 1974–P | 44 | Regulated |
| 16294100 | Waiahole Stream above Kamehameha Hwy, Oahu, HI | 10 | 21.482 | −157.846 | Windward | 2001–P | 15 | Regulated |
| 16294900 | Waikane Str at alt 75 ft at Waikane, Oahu, HI | 80 | 21.497 | −157.863 | Windward | 1960–P | 56 | Natural beginning 7/2015 |
| 16296500 | Kahana Str at alt 30 ft nr Kahana, Oahu, HI | 30 | 21.541 | −157.882 | Windward | 1959–P | 57 | Natural beginning 7/2015 |

**Table 6.** U.S. Geological Survey (USGS) continuous-record gaging stations in Hawai‘i in operation during water year 2018, with discharges available in the National Water Information System (NWIS) database.—Continued

| Station ID | Station name[1] | Altitude,[2] in feet | Latitude[3] | Longitude[3] | Aspect | Period of record | Years of record[4] | Flow classification |
|---|---|---|---|---|---|---|---|---|
| | | | | O‘ahu—Continued | | | | |
| 16301050 | Punaluu Str abv Punaluu Ditch Intake, Oahu, HI | 210 | 21.556 | −157.899 | Windward | 1953–P | 63 | Natural |
| 16304200 | Kaluanui Stream nr Punaluu, Oahu, HI | 110 | 21.586 | −157.908 | Windward | 1967–P | 51 | Natural |
| 16325000 | Kamananui Str at Pupukea Mil Rd, Oahu, HI | 590 | 21.620 | −158.015 | Leeward | 1963–2001, 2013–P (stage only) | 38 | Natural |
| 16330000 | Kamananui Str at Maunawai, Oahu, HI | 20 | 21.635 | −158.054 | Leeward | 1958–P | 60 | Regulated |
| 16343100 | Helemano Str at Joseph Leong Hwy, Haleiwa, Oahu, HI | 2 | 21.579 | −158.103 | Leeward | 2010–P (stage only) | 7 | Regulated |
| 16345000 | Opaeula Str nr Wahiawa, Oahu, HI | 1,120 | 21.562 | −158.000 | Leeward | 1959–P | 59 | Natural |
| | | | | Moloka‘i | | | | |
| 16400000 | Halawa Stream near Halawa, Molokai, HI | 210 | 21.156 | −156.762 | Windward | 1917–32, 1937–P | 93 | Natural |
| 16409000 | Waihanau Stream nr Kalaupapa, Molokai, HI | 2,250 | 21.157 | −156.958 | Windward | P (LF only) | 0 | Natural |
| 16414200 | Kaunakakai Gulch at altitude 75 feet, Molokai, HI | 80 | 21.096 | −157.018 | Leeward | 2003–P | 15 | Regulated |
| 16415000 | EF Kawela Gulch nr Kamalo, Molokai, HI | 3,620 | 21.110 | −156.903 | Leeward | 1946–71, P (LF only) | 24 | Natural |
| 16415600 | Kawela Gulch near Moku, Molokai, HI | 40 | 21.070 | −156.948 | Leeward | 2004–11, 2016–P | 9 | Regulated |
| 16417200 | Kainalu Stream nr Pauwalu, Molokai, HI | 290 | 21.095 | −156.779 | Leeward | P (LF only) | 0 | Natural |
| 16417800 | LB Honoulimaloo Str US diversion, Molokai, HI | 730 | 21.128 | −156.753 | Windward | P (LF only) | 0 | Natural |
| | | | | Maui | | | | |
| 16500800 | Kukuiula Gulch near Kipahulu, Maui, HI | 120 | 20.652 | −156.076 | Leeward | 1963–68, P (LF only) | 2 | Natural |
| 16501200 | Oheo Gulch at dam near Kipahulu, Maui, HI | 420 | 20.668 | −156.052 | Leeward | 1988–97, 2002–11, 2014–P | 22 | Natural |
| 16508000 | Hanawi Stream near Nahiku, Maui, HI | 1,320 | 20.807 | −156.114 | Windward | 1914–15, 1921–P | 96 | Natural |
| 16518000 | West Wailuaiki Stream near Keanae, Maui, HI | 1,550 | 20.814 | −156.143 | Windward | 1914–17, 1921–P | 97 | Natural |
| 16522950 | Piinaau Str 470 ft US Koolau Ditch, Maui, HI | 1,350 | 20.827 | −156.175 | Windward | P (LF only) | 0 | Natural |
| 16552800 | Waikamoi Str abv Kula PL intake nr Olinda, Maui, HI | 4,490 | 20.805 | −156.231 | Windward | 1953–68, 2009–P | 22 | Natural |
| 16587000 | Honopou Stream near Huelo, Maui, HI | 1,210 | 20.886 | −156.252 | Windward | 1911–P | 107 | Natural |
| 16604500 | Wailuku River at Kepaniwai Park, Maui, HI | 780 | 20.882 | −156.539 | Windward | 1983–P | 34 | Natural |

**Table 6.** U.S. Geological Survey (USGS) continuous-record gaging stations in Hawai‘i in operation during water year 2018, with discharges available in the National Water Information System (NWIS) database.—Continued

| Station ID | Station name[1] | Altitude,[2] in feet | Latitude[3] | Longitude[3] | Aspect | Period of record | Years of record[4] | Flow classification |
|---|---|---|---|---|---|---|---|---|
| | | | | Maui—Continued | | | | |
| 16614000 | Waihee Rv abv Waihee Dtch intk nr Waihee, Maui, HI | 600 | 20.936 | −156.547 | Windward | 1983–P | 33 | Natural |
| 16618000 | Kahakuloa Stream near Honokohau, Maui, HI | 330 | 20.979 | −156.554 | Windward | 1939–43, 1947–70, 1974–P | 68 | Natural |
| 16620000 | Honokohau Stream near Honokohau, Maui, HI | 870 | 20.962 | −156.588 | Windward | 1913–20, 1922–88, 1990–P | 99 | Natural |
| 16647000 | Ukumehame Gulch nr Olowalu, Maui, HI | 400 | 20.819 | −156.584 | Leeward | 1911, 1913–19, P (LF only) | 3 | Natural |
| | | | | Hawai‘i | | | | |
| 16704000 | Wailuku River at Piihonua, HI | 1,090 | 19.712 | −155.151 | Windward | 1928–P | 87 | Regulated prior to 1968 and after 5/1993 |
| 16717000 | Honolii Stream nr Papaikou, HI | 1,540 | 19.764 | −155.152 | Windward | 1911–13, 1967–P | 52 | Natural |
| 16717700 | Hakalau Stream nr alt 1300 ft, HI | 1,300 | 19.872 | −155.167 | Windward | P (LF only) | 0 | Natural |
| 16717815 | Manowaiopae Stream near Spencer Road, HI | 970 | 19.972 | −155.243 | Windward | P (LF only) | 0 | Natural |
| 16720000 | Kawainui Stream nr Kamuela, HI | 4,060 | 20.085 | −155.681 | Windward | 1964–P | 53 | Natural |
| 16725000 | Alakahi Stream near Kamuela, HI | 3,900 | 20.071 | −155.671 | Windward | 1964–P | 54 | Natural beginning 1997 |
| 16751500 | Awini Puali Gulch US of Kohala Ditch, HI | 1,000 | 20.192 | −155.748 | Windward | P (LF only) | 0 | Natural |
| 16757000 | Waikoloa Stream nr Kamuela, HI | 3,580 | 20.052 | −155.664 | Leeward | 1947–71, P (LF only) | 23 | Natural |
| 16759600 | Waiaha Stream at Holualoa, HI | 1,490 | 19.634 | −155.950 | Leeward | 2002–03, 2016–P | 2 | Natural |
| 16770500 | Paauau Gulch at Pahala, HI | 970 | 19.208 | −155.477 | Leeward | 1962–79, 2001–P | 33 | Natural |

[1]NWIS database limitations preclude the use of Hawaiian diacritical marks in USGS station names.

[2]Altitude values interpolated from USGS 1:24,000-scale digital hypsography data and rounded to the nearest ten.

[3]Latitude and longitude coordinates in North American Datum of 1983.

[4]Number of years of complete continuous record as of the end of 2018 water year. A water year is a 12-month period that extends from October 1 to September 30 of the following year and is named according to the year during which the period ends.

Surface-water use in Hawai‘i has also shifted to hydropower development in an effort to achieve 100 percent renewable energy in the electricity sector by 2045 (State of Hawai‘i, 2018a), as mandated by the State's renewable portfolio standards (Hawai‘i Revised Statutes § 269-92). In 2017, Hawai‘i generated about 27 percent of its total energy from renewable sources of which 2.4 percent was from hydropower. Hawai‘i island and Kaua‘i lead in hydropower development, contributing about 96 percent of the total installed hydropower capacity in the State. Two hydropower projects are currently under development in west Kaua‘i—a hydropower expansion facility in Olokele and a pumped storage hydropower facility in Kekaha— that could potentially double the hydropower capacity in the State (State of Hawai‘i, 2018b).

**Table 7.** U.S. Geological Survey (USGS) partial-record stations in Hawai‘i in operation during water year 2018, with discharges available in the National Water Information System (NWIS) database.

[abv, above; alt, altitude; conf, confluence; DS, downstream; Dt, ditch; ft, feet; Gl, Gulch; HI, Hawaii; Hwy, Highway; LB, left branch; mi, mile; N., North; NF, North Fork; nr, near; P, present (2018); RB, Right Branch; Rd, Road; Res, Reservoir; S, South; SF, South Fork; Str, Stream; SW, Southwest; trib, tributary; US, upstream; W, West]

| Station ID | Station name[1] | Altitude,[2] in feet | Latitude[3] | Longitude[3] | Aspect | Period of record |
|---|---|---|---|---|---|---|
| Kaua‘i | | | | | | |
| 215538159292301 | Poeleele Stream at Kaumualii Hwy, Kauai, HI | 440 | 21.927 | −159.490 | Leeward | 2016–P |
| 215608159285801 | Omao Stream at Kaumualii Hwy, Kauai, HI | 550 | 21.936 | −159.483 | Leeward | 1939–1940, 2016–P |
| 215751159283901 | Kuia Str trib 1 mi SW of Papuaa Res, Kauai, HI | 680 | 21.964 | −159.478 | Leeward | 2016–P |
| 215751159311801 | Wahiawa Stream US Alexander Res, Kauai, HI | 1,720 | 21.966 | −159.521 | Leeward | 2017–P |
| 215751159311901 | Wahiawa Str 330ft US Alexander Res, Kauai, HI | 1,620 | 21.964 | −159.522 | Leeward | 2017–P |
| 215754159311601 | LB Wahiawa Str 400 ft US Alexander Res, Kauai, HI | 1,640 | 21.965 | −159.521 | Leeward | 2017–P |
| 215833159232601 | Nawiliwili Stream at Rapoza Rd., Kauai, HI | 230 | 21.976 | −159.391 | Leeward | 2017–P |
| 215851159273901 | Kamooloa Str US Papuaa Res intake, Kauai, HI | 550 | 21.981 | −159.461 | Leeward | 2016–P |
| 215853159281801 | Paohia Str US Koloa Ditch, Kauai, HI | 750 | 21.981 | −159.472 | Leeward | 2016–P |
| 215949159225801 | Hanamaulu Str US Kapaia Ditch, Kauai, HI | 240 | 21.997 | −159.383 | Windward | 2016–P |
| 215952159230501 | Hanamaulu trib 0.16 US Kapaia Ditch, Kauai, HI | 270 | 21.998 | −159.385 | Windward | 2016–P |
| 220037159242901 | Hanamaulu Str 0.6 mi US S Kapaia Res, Kauai, HI | 490 | 22.010 | −159.408 | Windward | 2016–P |
| 220054159244001 | Hanamaulu Str 1 mi US N Kapaia Res, Kauai, HI | 500 | 22.015 | −159.411 | Windward | 2016–P |
| 220224159282301 | Iliiliula Str trib 4 US N Wailua Ditch, Kauai, HI | 1,060 | 22.040 | −159.473 | Windward | 2016–P |
| 220325159275401 | SF Waikoko Str US Iliiliula N Wailua Dt, Kauai, HI | 1,110 | 22.057 | −159.465 | Windward | 2016–P |
| 220326159275401 | NF Waikoko Str US Iliiliula N Wailua Dt, Kauai, HI | 1,110 | 22.057 | −159.465 | Windward | 2016–P |
| 220346159280601 | NF Wailua River US Blue Hole intake, Kauai, HI | 1,100 | 22.063 | −159.468 | Windward | 2016–P |
| 220423159235501 | RB Opaekaa Stream 0.3 mi US of LB, Kauai, HI | 470 | 22.073 | −159.399 | Windward | 2016–P |
| 221118159295701 | Waioli Stream 1.5 mi US str mouth, Kauai, HI | 40 | 22.188 | −159.499 | Windward | Station established in 2018 |
| 221111159203401 | Moloaa Stream at Koolau Rd, Kauai, HI | 70 | 22.187 | −159.343 | Windward | Station established in 2018 |
| 220427159384501 | Koaie Str US Kekaha Ditch intake, Kauai, HI | 780 | 22.074 | −159.646 | Leeward | Station established in 2018 |
| O‘ahu | | | | | | |
| 213846157594401 | Oio Str at Drum Rd lower crossing, Oahu, HI | 1,190 | 21.646 | −157.995 | Windward | 1945, 1965–66, P |
| 213943157584201 | Ohiaai Gl at Charlie Rd, Oahu, HI | 380 | 21.662 | −157.978 | Windward | Station established in 2018 |
| 16270900 | Luluku Str at alt 220 ft nr Kaneohe, Oahu, HI | 220 | 21.392 | −157.809 | Windward | 1963, 1965, 1966–98 |
| 16265700 | Kamooalii Str at alt 200 ft nr Kaneohe, Oahu, HI | 200 | 21.383 | −157.796 | Windward | 1959, 1983, 1985–98, 2006, P |
| 211803157452101 | Wailupe Gulch, 650 ft U/S of debris dam, Oahu, HI | 270 | 21.301 | −157.756 | Leeward | 2008, P |
| 212559159551701 | Waimano Str N trib abv Waimano Falls, Oahu, HI | 560 | 21.433 | −157.922 | Leeward | P |
| 16335000 | Kawainui Stream above Kamananui Ditch, Oahu, HI | 740 | 21.580 | −158.003 | Leeward | 1960–61, 1963, P |
| Moloka‘i | | | | | | |
| 210530156471201 | Honomuni Gl nr alt. 250 ft, Molokai, HI | 250 | 21.092 | −156.787 | Leeward | P |
| 210631156460301 | Waialua Stream nr alt. 300 ft, Molokai, HI | 300 | 21.109 | −156.768 | Windward | P |

**Table 7.** U.S. Geological Survey (USGS) partial-record stations in Hawai‘i in operation during water year 2018, with discharges available in the National Water Information System (NWIS) database.—Continued

| Station ID | Station name[1] | Altitude,[2] in feet | Latitude[3] | Longitude[3] | Aspect | Period of record |
|---|---|---|---|---|---|---|
| Moloka‘i—Continued | | | | | | |
| 210645156542501 | W Fork Kawela US diversion nr 3685 ft, Molokai, HI | 3,680 | 21.112 | −156.907 | Leeward | 2010, P |
| 210706156544801 | LB SF Kaunakakai Gl nr alt. 3650 ft, Molokai, HI | 3,650 | 21.118 | −156.913 | Leeward | P |
| 210723156461301 | Honouliwai Str nr alt. 1200 ft, Molokai, HI | 1,200 | 21.123 | −156.770 | Windward | P |
| 210725156550501 | RB SF Kaunakakai Gl nr alt. 3500 ft, Molokai, HI | 3,500 | 21.124 | −156.918 | Leeward | P |
| 210815156451801 | Papio Gulch nr alt. 1100 ft, Molokai, HI | 1,100 | 21.138 | −156.755 | Windward | P |
| 210833156582501 | Kuhuaawi Gulch at alt 1900 ft, Molokai HI | 1,900 | 21.143 | −156.974 | Leeward | P |
| Maui | | | | | | |
| 203901156050901 | Alelele Stream above Hana Hwy, Maui, HI | 100 | 20.650 | −156.086 | Leeward | P |
| 204026156022601 | Hahalawe Gl at Hana Hwy, Maui, HI | 340 | 20.674 | −156.040 | Leeward | 1969, 1984 |
| 204113156004001 | Papahawahawa Gulch at Hana Hwy, Maui, HI | 130 | 20.687 | −156.011 | Leeward | P |
| 204129156025901 | Wailua Str 0.33mi DS Waihiumalu Falls, Maui, HI | 1,040 | 20.691 | −156.050 | Leeward | P |
| 204756156040401 | Lanikele Gulch at Hana Hwy, Maui, HI | 740 | 20.799 | −156.068 | Windward | Station established in 2018 |
| 204804156043901 | Kahawaihapapa Gulch at Hana Hwy, Maui, HI | 860 | 20.801 | −156.077 | Windward | Station established in 2018 |
| 204820156050001 | Kalepalehua Gulch at Hana Hwy, Maui, HI | 870 | 20.806 | −156.083 | Windward | Station established in 2018 |
| 204946156092101 | Palauhulu Str 0.9 mi DS Kano Str conf, Maui, HI | 760 | 20.830 | −156.156 | Windward | Station established in 2018 |
| 205121156321101 | Waikapu Str 120ft US S Waikapu Dt intake, Maui, HI | 1,160 | 20.856 | −156.536 | Leeward | P |
| 205427156312901 | South Waiehu Stream above intake, Maui, HI | 620 | 20.907 | −156.525 | Windward | P |
| 205458156315401 | North Waiehu Stream above intake, Maui, HI | 660 | 20.910 | −156.526 | Windward | P |
| Hawai‘i | | | | | | |
| 201222155472801 | Waiakauaua Gl 100 ft US of access road, HI | 1,010 | 20.206 | −155.791 | Windward | P |
| 201251155444801 | Niulii Stream US of access road bridge, HI | 350 | 20.214 | −155.747 | Windward | P |
| 195939155173301 | Kaula Gulch nr alt 1,400 ft, HI | 1,400 | 19.994 | −155.293 | Windward | Station established in 2018 |
| 195732155135601 | Kaiwilahilahi Stream at alt 1,100 ft, HI | 1,100 | 19.959 | −155.232 | Windward | P |
| 195647155123901 | Paeohe Stream nr Maulua Bay, HI | 1,070 | 19.946 | −155.212 | Windward | Station established in 2018 |
| 195622155120801 | Makahiloa Stream at alt 920 ft, HI | 920 | 19.940 | −155.202 | Windward | Station established in 2018 |
| 195512155105801 | Waikaumalo Stream at road crossing, HI | 1,140 | 19.920 | −155.183 | Windward | Station established in 2018 |
| 195400155091501 | Umauma Stream nr alt 630 ft, HI | 630 | 19.900 | −155.154 | Windward | Station established in 2018 |
| 195321155100301 | Kamaee Stream 2.7 mi west of Hakalau, HI | 1,120 | 19.889 | −155.168 | Windward | Station established in 2018 |
| 195056155100801 | Kolekole Stream nr alt 1,650 ft, HI | 1,650 | 19.848 | −155.170 | Windward | P |
| 195044155082801 | Honomu Stream at alt 1,050 ft, HI | 1,050 | 19.846 | −155.141 | Windward | P |
| 194901155090101 | Kawainui Stream nr alt 1,600 ft, HI | 1,600 | 19.817 | −155.150 | Windward | Station established in 2018 |

**Table 7.** U.S. Geological Survey (USGS) partial-record stations in Hawaiʻi in operation during water year 2018, with discharges available in the National Water Information System (NWIS) database.—Continued

| Station ID | Station name[1] | Altitude,[2] in feet | Latitude[3] | Longitude[3] | Aspect | Period of record |
|---|---|---|---|---|---|---|
| | | | Hawaiʻi—Continued | | | |
| 194831155073601 | Hanawi Stream nr alt 900 ft, HI | 900 | 19.809 | −155.127 | Windward | Station established in 2018 |
| 16756000 | Kohakohau Stream near Kamuela, HI | 3,510 | 20.048 | −155.680 | Leeward | 1956–66 (continuous), station established in 2018 as partial record site |
| 200517155441801 | Keawewai Stream near Puu Ahia, HI | 4,680 | 20.088 | −155.738 | Leeward | 1963, station established in 2018 as partial record site |
| 200555155450801 | Waipahoehoe Stream nr Puu Lapalapa, HI | 4,230 | 20.098 | −155.753 | Leeward | 1963, station established in 2018 as partial record site |

[1]NWIS database limitations preclude the use of Hawaiian diacritical marks in USGS station names.

[2]Altitude values interpolated from USGS 1:24,000-scale digital hypsography data and rounded to the nearest ten.

[3]Latitude and longitude coordinates in North American Datum of 1983.

## Surface-Water Availability During Low-Flow Conditions

The amount of surface water available during low-flow conditions may become insufficient to meet all competing demands. Inadequate streamflow poses a threat to the survival of native stream animals by reducing available instream habitats and in some streams, by eliminating continuous flow to the ocean for extended periods. Water quality may become a concern during low-flow conditions, and streamflow information is needed to characterize contaminant loading associated with low-flow conditions. In areas where groundwater discharges to streams, increasing groundwater withdrawals can affect streamflow, depending on the rate of withdrawal and the proximity of the pumped wells to the streams.

Documentation of natural (unregulated) low-flow conditions—streamflow that is not affected by mainly surface-water diversions, irrigation return flows, or groundwater withdrawal that has been known to reduce streamflow—is important for identifying critical areas that affect both mankind and aquatic species, and for developing plans to mitigate further effects to the surface-water resource. Although USGS has operated hundreds of continuous-record streamflow-gaging stations in Hawaiʻi since the early 1900s, information on natural flows for many streams is unavailable because many of the gaging stations were located downstream of surface-water diversions and monitored regulated flow, or were operated for only short periods (Fontaine, 1996). The USGS, with funding from various State agencies, has conducted studies to quantify surface-water availability during low-flow conditions for particular regions of interest where streams are ungaged (Gingerich, 2005; Oki and others, 2010; Cheng and Wolff, 2012; Cheng, 2014).

## Regulatory Developments

Allocation of the limited water resources for instream and offstream uses is a major challenge in Hawaiʻi. The diversion of surface water for offstream uses reduces flow in the downstream reaches, which can adversely affect traditional Hawaiian practices, stream ecology, water quality, recreational activities, and aesthetics. Addressing Native Hawaiian water rights and ecosystem requirements highlights the need to quantify instream and offstream uses of available surface-water resources.

### Instream-Flow Standards

The State Water Code mandates that CWRM establish a statewide instream-use protection program (State Water Code, Hawaiʻi Revised Statutes, chapter 174C, section 71). The principal mechanism that CWRM implements for the purpose of protecting instream uses is the establishment of instream-flow standards that describe the flows necessary to protect the public interest in the stream with consideration of existing and potential water developments, including the economic effect of restricting such use (State Water Code, Hawaiʻi Revised Statutes, chapter 174C, section 71[1][C]). The instream uses recognized by CWRM are (1) maintenance of fish and wildlife habitat; (2) outdoor recreational activities; (3) maintenance of ecosystems; (4) aesthetic values, such as waterfalls and scenic waterways; (5) maintenance of water quality; (6) the conveyance of irrigation and domestic water supplies; and (7) the protection of traditional and customary Hawaiian rights.

The CWRM first adopted interim instream-flow standards for all Hawaiian streams in 1988 and 1989. These interim

instream-flow standards did not have quantitative flow values and allowed diversions existing at the time of the adoption to continue operating. Additional information could be filed with CWRM to reduce or increase diversion, through a modification of the interim instream-flow standards. Quantitative interim instream-flow standards that account for economic, cultural, ecologic, recreational, and aesthetic needs have been established for less than 50 streams in Hawaiʻi (table 8).

### Surface-Water Management Area

When contentious disputes over the use of surface-water resources in an area occur, CWRM may designate the area as a surface-water management area after appropriate investigations and consultation with various relevant agencies and parties. The CWRM regulates the use of surface water within the management area by requiring all surface-water users to obtain surface-water use permits to withdraw water for various purposes. Existing surface-water uses are typically evaluated before new uses, and all surface-water uses must be proven reasonable and beneficial. The State Water Code (Hawaiʻi Revised Statutes, chapter 174C, section 71[1][C]) defines reasonable-beneficial use as, ". . .the use of water in such a quantity as is necessary for economic and efficient utilization, for a purpose, and in a manner which is both reasonable and consistent with the state and county land use plans and the public interest."

As of 2018, CWRM has designated one surface-water management area in Hawaiʻi. The stream basins of Waiheʻe River, Waiehu Stream, Wailuku River, and Waikapū Stream on Maui were designated as a surface-water management area on April 30, 2008, hereafter referred to as the Nā Wai ʻEhā surface-water management area. Surface-water uses existing at the time of designation and new surface-water uses within the management area require surface-water use permits to be obtained from the CWRM. A process to recognize and determine appurtenant rights to the water in this management area was adopted by CWRM in September 2011. As of November 2018, existing uses, new uses, and appurtenant rights to the water in the Nā Wai ʻEhā surface-water management area are being addressed in a contested case (State of Hawaiʻi, 2017b).

### Revocable Permits and Water Leases

Revocable permits issued by the Board of Hawaiʻi Department of Land and Natural Resources (DLNR) allow the temporary uses of water on State lands if these uses serve the public interests (Hawaiʻi Revised Statutes, Section 171-58). The permits are issued on a month-to-month basis and are subject to a maximum term of one year and other restrictions under the law. In 2016, the DLNR Revocable Permit Task Force recommended that the permits be converted to long-term water leases. The new guidance for acquiring a long-term water lease requires compliance with the State's environmental regulations (Hawaiʻi Revised Statutes, Chapter 343), consultation with Hawaiʻi Department of Hawaiian Home Lands (DHHL) regarding water quantities, appraisal, and public auction prior to approval by the Board of DLNR. The Board of DLNR has indicated the importance of real-time monitoring of streams supporting water leases (Ayron Strauch, CWRM, oral commun., 2019).

# Data-Collection Strategies

The USGS collects streamflow data at three primary types of measurement sites: (1) continuous-record station, (2) partial-record station, and (3) miscellaneous measurement site. Collectively, these measurement sites are the main components of the data-collection strategies that USGS employs to provide useful information for the management and protection of surface-water resources statewide. The surface-water data-collection strategies comprise (1) long-term monitoring at selected sites for the purposes of evaluating trends in streamflow and characterizing regional hydrology; and (2) occasional intensive monitoring at selected sites to enhance spatial understanding of hydrologic conditions and interactions between hydrologic systems, and to address current issues in surface-water priority areas.

## Long-Term Monitoring

Long-term monitoring is achieved through continuous-record stations that provide discharge on a continuous basis (for example, at 15-minute intervals) at a selected location. Continuous-record stations are typically located in stream channels to monitor stream discharge, but they also can be located in diversion systems to monitor diverted flow. Long-term data from continuous-record stations located in stream channels that have limited or no substantial human-made changes provide a baseline for evaluating streamflow trends and characterizing regional hydrology.

### Streamflow Characteristics

Characteristics of streamflow are commonly described using the mean or average value of flow for a particular time scale (for example, daily, monthly, or yearly). Mean streamflow varies with the period of record from which it is computed mainly because of variations in rainfall. Complete water years of record are preferred when computing streamflow characteristics. A water year is a 12-month period that extends from October 1 to September 30 and is named according to the year the period ends. For example, the "water year 2018" is the period October 1, 2017, to September 30, 2018.

Fontaine (1996, p. 19–21) used data from 5 long-term, continuous-record streamflow-gaging stations on Oʻahu, each with more than 60 years of record, and demonstrated that estimates of streamflow characteristics are improved with increased record length from which the statistics are computed. Data from long-term stations that monitor natural flow for 30 or more years can be used to compute streamflow characteristics that are representative of long-term streamflow conditions.

**Table 8.** Streams with quantitative interim instream-flow standards that have been amended from standards adopted in 1988 and 1989.

[>, greater than; ≤, less than or equal to]

<table>
<tr><th rowspan="2">Stream name</th><th rowspan="2">Location description</th><th colspan="2">Interim instream-flow standard, in million gallons per day</th><th rowspan="2">Year of designation</th></tr>
<tr><th>Phase 1</th><th>Phase 2[1]</th></tr>
<tr><td colspan="5">Kaua‘i</td></tr>
<tr><td>Kōke‘e Stream</td><td>Downstream from Kōke‘e Ditch intake</td><td>Natural flow</td><td>Natural flow (if streamflow ≤ 1.2); 1.2 (if streamflow > 1.2)</td><td>2017</td></tr>
<tr><td>Kauaikananā Stream</td><td>Downstream from Kōke‘e Ditch intake</td><td>0.7</td><td>2/3 of streamflow (if streamflow ≤ 1.2); 0.6 (if streamflow > 1.2)</td><td>2017</td></tr>
<tr><td>Kawaikōī Stream</td><td>Downstream from Kōke‘e Ditch intake</td><td>4.9</td><td>2/3 of streamflow (if streamflow ≤ 6.4); 4.0 (if streamflow > 6.4)</td><td>2017</td></tr>
<tr><td>Waiakōali Stream</td><td>Downstream from Kōke‘e Ditch intake</td><td>1.4</td><td>2/3 of streamflow (if streamflow ≤ 1.3); 0.8 (if streamflow > 1.3)</td><td>2017</td></tr>
<tr><td>Koai‘e Stream</td><td>Downstream from Kekaha Ditch intake</td><td>2.0</td><td>2.0</td><td>2017</td></tr>
<tr><td>Waimea River</td><td>Downstream from Waimea Ditch intake</td><td>8.0</td><td>8.0</td><td>2017</td></tr>
<tr><td>Waimea River</td><td>At USGS streamflow-gaging station 16031000</td><td>25.0</td><td>25.0</td><td>2017</td></tr>
<tr><td colspan="5">O‘ahu</td></tr>
<tr><td>Waiāhole Stream</td><td>Not specified</td><td colspan="2">8.7</td><td>2006</td></tr>
<tr><td>Waianu Stream</td><td>Not specified</td><td colspan="2">3.5</td><td>2006</td></tr>
<tr><td>Waikāne Stream</td><td>Not specified</td><td colspan="2">3.5</td><td>2006</td></tr>
<tr><td>Kahana Stream</td><td>Not specified</td><td colspan="2">13.3</td><td>2006</td></tr>
<tr><td colspan="5">Maui</td></tr>
<tr><td>Waihe‘e River</td><td>Downstream from Spreckels Ditch intake</td><td colspan="2">14.0</td><td>2014</td></tr>
<tr><td>Waihe‘e River</td><td>Stream mouth</td><td colspan="2">10.0</td><td>2014</td></tr>
<tr><td>North Waiehu Stream</td><td>Downstream from Waihe‘e Ditch intake</td><td colspan="2">1.0</td><td>2014</td></tr>
<tr><td>South Waiehu Stream</td><td>Downstream from Spreckels Ditch intake</td><td colspan="2">0.9</td><td>2010</td></tr>
<tr><td>Waiehu Stream</td><td>Stream mouth</td><td colspan="2">0.6</td><td>2010, 2014</td></tr>
<tr><td>Wailuku River</td><td>Downstream from ‘Īao-Waikapu and ‘Īao-Maniania Ditch intakes</td><td colspan="2">10.0</td><td>2010, 2014</td></tr>
<tr><td>Wailuku River</td><td>Stream mouth</td><td colspan="2">5.0</td><td>2010, 2014</td></tr>
<tr><td>Waikapū Stream</td><td>Downstream from South Waikapū Ditch intake</td><td colspan="2">2.9</td><td>2014</td></tr>
<tr><td>Ukumehame Gulch</td><td>Downstream from diversion dam at altitude 220 feet</td><td colspan="2">2.9</td><td>2018</td></tr>
<tr><td>Olowalu Stream</td><td>At discontinued USGS streamflow-gaging station 16646200</td><td colspan="2">2.33</td><td>2018</td></tr>
<tr><td>Launiupoko Stream</td><td>Downstream from diversion at altitude 1,340 feet</td><td colspan="2">0</td><td>2018</td></tr>
<tr><td>Kaua‘ula Stream</td><td>Downstream from Kaua‘ula Ditch intake at altitude 1,540 feet</td><td colspan="2">3.36</td><td>2018</td></tr>
<tr><td>Kaua‘ula Stream</td><td>Downstream from kuleana users near altitude 270 feet</td><td colspan="2">4.1</td><td>2018</td></tr>
<tr><td>Kanahā Stream</td><td>Near altitude of 1,100 feet downstream from MDWS diversion intake</td><td colspan="2">0.80</td><td>2018</td></tr>
<tr><td>Kahoma Stream</td><td>At altitude of 1,850 feet downstream from Kahoma Ranch diversion intake</td><td colspan="2">3.49</td><td>2018</td></tr>
<tr><td>Honopou Stream</td><td>Downstream from Hāna highway</td><td colspan="2">Full restoration[2]</td><td>2018</td></tr>
<tr><td>Huelo Stream</td><td>Downstream of Ha‘ikū Ditch</td><td colspan="2">Full restoration[2]</td><td>2018</td></tr>
<tr><td>Hanehoi Stream</td><td>Upstream of Lowrie Ditch</td><td colspan="2">Full restoration[2]</td><td>2018</td></tr>
<tr><td>Waikamoi Stream</td><td>Upstream from Hāna Highway</td><td colspan="2">2.46</td><td>2018</td></tr>
</table>

**Table 8.** Streams with quantitative interim instream-flow standards that have been amended from standards adopted in 1988 and 1989.—Continued

| Stream name | Location description | Interim instream-flow standard, in million gallons per day | Year of designation |
|---|---|---|---|
| Maui—Continued | | | |
| Wahinepeʻe Stream | Upstream from Hāna Highway | 0.58 | 2018 |
| Puohokamoa Stream | Downstream from Hāna Highway | 0.71 | 2018 |
| Haʻipuaʻena Stream | Downstream from Hāna Highway | 0.88 | 2018 |
| Punalau Stream | Upstream from Hāna Highway | 1.88 | 2018 |
| Honomanū Stream | Upstream from Hāna Highway | 2.72 | 2018 |
| Nuaʻailua Stream | To be determined | 1.42 | 2018 |
| Piʻinaʻau Stream | Upstream from Hāna Highway | Full restoration[2] | 2018 |
| Palauhulu Stream | Upstream from Hāna Highway | Full restoration[2] | 2018 |
| Waiokamilo Stream | Downstream from Koʻolau Ditch intake | Full restoration[2] | 2018 |
| ʻŌhia Stream | Not specified | Full restoration[2] | 2018 |
| Wailuanui Stream | At Hāna Highway | Full restoration[2] | 2018 |
| West Wailua Iki Stream | Upstream from Hāna Highway | Full restoration[2] | 2018 |
| East Wailua Iki Stream | At Hāna Highway | 2.39 | 2018 |
| Kopiliula Stream | Downstream from Hāna Highway | 2.07 | 2018 |
| Puaʻakaʻa Stream | Upstream from Hāna Highway | 0.13 | 2018 |
| Waiohue Stream | At Hāna Highway | Full restoration[2] | 2018 |
| Paʻakea Stream | At Hāna Highway | 0.12 | 2018 |
| Waiaaka Stream | Upstream from Hāna Highway | 0.50 | 2018 |
| Kapaula Gulch | At Koʻolau Ditch intake | 0.36 | 2018 |
| Hanawī Stream | Downstream from Hāna Highway | 0.60 | 2018 |
| Makapipi Stream | Upstream from Hāna Highway | Full restoration[2] | 2018 |

[1]Phase 2 interim instream-flow standards will be effective if and when Kauaʻi Island Utility Cooperative (KIUC) develops planned renewable energy projects (State of Hawaiʻi, 2017a).

[2]Stream is to be restored to natural, undiverted base flows ("full restoration"), meaning all the water that was historically available to the communities along each specific stream before the East Maui Irrigation (EMI) System was built. If, under current climate, rainfall, and streamflow conditions, such streamflows are insufficient to meet all irrigation and domestic uses, it is incumbent upon such users to develop a system of reasonable sharing, including adequate stream flows for resuscitation of stream life (State of Hawaiʻi, 2016c).

## Streamflow Trends

Understanding long-term trends and variations in streamflow are important for the proper management of Hawaiʻi's surface-water resources. Streamflow-trend analyses typically include characterizing trends in total streamflow and base flow, describing any apparent regional patterns in trends, and identifying hydrologic and climatic factors that may be related to the observed trends (Oki, 2004). Variability in streamflow can also result from land-use changes, including but not limited to changes in forest cover, agriculture, urban development, and highway construction. Understanding trends could help water users and resource managers to plan and prepare for changes in surface-water availability for instream and offstream uses during periods of short-term climate variability, such as droughts, and sustained climate changes that may affect surface-water availability for extended periods. The most recent evaluation of streamflow trends in Hawaiʻi was done by Clilverd and others (2019).

Continuous-record streamflow-gaging stations that are useful in identifying long-term trends should satisfy two important criteria: (1) drainage basins upstream from the stations are not affected by land-cover changes, and (2) stations are located in a variety of physical and climatologic settings that are representative of the variability of hydrologic characteristics in Hawaiʻi (Fontaine, 1996, p. 21). In effect, continuous-record stations used for trend analysis should monitor natural streamflow. In addition, accuracy of the streamflow characteristics computed from continuous-record stations increases with the length of record from which the streamflow characteristics are computed.

### Regional Hydrology

Regional hydrology refers to methods that use streamflow and other hydrologic data (for example, drainage area, slope, soil types, and rainfall) from a representative number of sites to estimate streamflow characteristics at sites with minimal or no streamflow data within a given region. These methods provide regional estimates of streamflow characteristics by characterizing streamflow data at ungaged sites or relating data from long-term stations to data from short-term stations or discrete data from the stations of interest (record augmentation). Statistical regression analysis of drainage-basin characteristics and streamflow (regional regression) can also be used to estimate streamflow characteristics in a region. Accurate regional estimates of streamflow characteristics require streamflow data from long-term continuous-record stations that monitor natural flow and are located in a variety of hydrologic settings. Long-term stations that monitor regulated flow can be used only if concurrent diverted flows are available to allow reconstruction of the natural streamflow record at the stations.

Low-flow investigations of Hawaiian streams have been conducted to evaluate changes in flow for streams with significant land-use changes or surface-water diversions. A majority of these investigations were conducted on a basin scale with a focus on computing low-flow characteristics, examining the effects of surface-water diversions on low flows, and, in some instances, examining habitat availability for native stream fauna (Fontaine, 2003; Gingerich, 2005; Gingerich and Wolff, 2005; Oki and others, 2010; Cheng and Wolff, 2012; Cheng, 2014). Statewide analysis of low flows includes studies by Yamanaga (1972), Fontaine and others (1992), Cheng (2016), Bassiouni and Oki (2013), and Clilverd and others (2019). For many of these studies, accuracy of the discharge estimates could be improved with longer periods of record at active continuous-record stations and additional continuous-record stations in areas with little or no streamflow data, such as Moloka‘i and Hawai‘i island, and leeward areas of all Hawaiian Islands.

Results from studies that use regional hydrology methods for estimating streamflow characteristics could be used to strategically and economically expand the current long-term continuous-record station network. These studies often identify under-represented areas that need additional data collection, which could be achieved by reactivating a discontinued continuous-record station, converting a partial-record site to a continuous-record station, or installing a new continuous-record station at an ungaged site. The decision to operate a continuous-record station in these under-represented areas depends on the types of streamflow data available for hydrologically similar streams, the streamflow characteristics of interest, and the quality of the statistical relations between stations. A discontinued short-term continuous-record station that monitored natural flow could be considered for reactivation if it continues to monitor natural streamflow, especially within a surface-water priority area, and its short-term record has been shown to poorly correlate with long-term records from continuous-record stations on the island. Poor statistical correlation with records from other long-term stations is a reasonable justification for long-term continuous-record data to be collected at a site because other means to accurately characterize streamflow at the site currently are not available. Conversely, it may be unnecessary to collect continuous-record data at a partial-record site if the partial-record data have been shown to highly correlate with data from long-term continuous-record stations.

Cheng (2016, tables 3–7) summarized natural low-flow characteristics at continuous-record streamflow-gaging stations and partial-record stations on Kaua‘i, O‘ahu, Moloka‘i, Maui, and Hawai‘i island. Inactive stations with low-flow estimates rated as poor were considered for reactivation.

## Occasional Intensive Monitoring

Occasional intensive monitoring is achieved through (1) short-term continuous stations, which monitor flow conditions continuously for a short period of time—usually for the duration of the study under which the stations are established; (2) partial-record stations, which commonly have 10 or more systematic streamflow measurements at a location in the stream; and (3) miscellaneous sites, which typically have less than 10 streamflow measurements that may not have been collected in a systematic manner as with a partial-record station. For water-availability studies, a short-term continuous low-flow station can be operated in the specific area of interest if no data exist in hydrologically similar areas. Partial-record stations and miscellaneous sites are less costly relative to operating a continuous-record station and allow streamflow information to be collected in a specific area of interest where continuous-record data may not be needed. These types of measurement sites are commonly used to describe hydrology in under-represented areas (data gaps), quantify availability of low flows at a stream site, and characterize the distribution of flow along a stream.

### Low-Flow Estimates

Surface-water resources in an area must be quantified as part of evaluating existing uses and potential climate-change effects on the resources supporting future uses. Because the cost of maintaining continuous-record stations at all sites of interest on all streams is prohibitive, partial-record stations offer a cost-effective way of expanding the geographic coverage of low-flow information (Curran and others, 2012). Partial-record stations commonly are used to estimate low-flow characteristics at sites without a long-term continuous-record station and can also provide additional data that can be used to develop regression models for estimating low-flow characteristics at ungaged sites, although the errors associated with flow estimates based on partial-record measurements are greater than those computed from continuous-record stations.

Low-flow discharges are estimated using record-augmentation methods that relate discharge measurements at the partial-record stations to concurrent daily mean discharges at

nearby continuous-record stations (index stations). In areas where hydrologic data are limited or do not exist, a short-term continuous station can be established as a potential index station for the partial-record stations. The statistical relation between data from a continuous station and a partial-record station can be assumed to remain constant over time if the hydrogeologic and morphologic characteristics of the stream basin and climatologic conditions remain unchanged. Extreme hydrologic events can alter the morphological characteristics of the stream channel and potentially its flow. If such an extreme event takes place, then additional discharge measurements at the partial-record site are needed to evaluate the validity of the statistical relation. Spatial changes in climatologic conditions can also affect the statistical relation.

### Seepage Analysis

A seepage run can be used to quantify the spatial distribution of flow along a stream. During a seepage run, same-day discharge measurements are made at selected sites along the stream during stable-flow conditions to determine the magnitude of streamflow gains and losses and to document stream reaches that are either flowing or dry. Different reaches of the same stream can either gain water (groundwater discharge into stream) or lose water (stream discharge into groundwater body), depending on the position of the water table relative to the streambed. When coupled with low-flow discharge estimates at sites along the same stream, results of a seepage run can provide natural water-availability information for stream reaches and help determine whether the stream flows continuously from the mountain to the ocean (mauka to makai flow).

Because results of a seepage analysis provide information on the interaction between surface water and groundwater, they can also be used to support certain conceptual models of groundwater occurrence and flow as discussed in the “Setting” for the “Groundwater” section of this report. Stream reaches in the dike-impounded-groundwater and thickly saturated settings gain water where groundwater discharges to streams. Most stream reaches located over the freshwater-lens setting lose water as the water in the stream seeps into the ground; the exception is near the coast where the freshwater lens discharges to lower stream reaches and springs. Although surface water and groundwater are managed separately, characterizing surface water and groundwater interactions is important for integrated water-resource management.

## Surface-Water Monitoring Program

The surface-water monitoring program consists of 96 active continuous stations, 45 active partial-record stations, 46 additional continuous stations, and 14 additional partial-record stations (table 9). Additional stations are either new or inactive (discontinued) stations that are reactivated to supplement the current program. Maps showing locations of the monitoring stations are developed for the monitoring program with the

**Table 9.** Summary of data-collection sites in the surface-water resource-monitoring program for Hawai‘i.

[CWRM, State of Hawai‘i Commission on Water Resource Management; USGS, U.S. Geological Survey]

| Station type | Kaua‘i | O‘ahu | Moloka‘i | Maui | Hawai‘i | Statewide |
|---|---|---|---|---|---|---|
| Number of surface-water monitoring stations active during 2018 | | | | | | |
| Continuous, unregulated flow[1] | 8 | 17 | 5 | 14 | 9 | 53 |
| Continuous, regulated flow[1] | 3 | 15 | 1 | 2 | 1 | 22 |
| Continuous, unregulated flow[2] | 0 | 1 | 0 | 1[3] | 0 | 1 |
| Continuous, regulated flow[2] | 2 | 1 | 1 | 16 | 0 | 20 |
| Partial record, unregulated flow[1] | 3 | 6 | 8 | 11 | 16 | 44 |
| Partial record, regulated flow[1] | 0 | 1 | 0 | 0 | 0 | 1 |
| Total | 16 | 41 | 15 | 44 | 26 | 142 |
| Number of additional stations identified as needed, by type | | | | | | |
| Continuous, unregulated flow | 3 | 2 | 3 | 8 | 4 | 20 |
| Continuous, regulated flow | 6 | 5 | 2 | 12 | 1 | 26 |
| Partial record, unregulated flow | 5 | 5 | 0 | 1 | 3 | 14 |
| Partial record, regulated flow | 0 | 0 | 0 | 0 | 0 | 0 |
| Total | 14 | 12 | 5 | 21 | 8 | 60 |
| Total number of stations selected for the surface-water program | 30 | 53 | 20 | 67 | 34 | 205 |

[1]Stations operated by USGS

[2]Stations operated by CWRM

[3]Both USGS and CWRM operate independent monitoring stations at the same location on Ukumehame Gulch

combined networks. Site selection of additional monitoring stations considers many factors including access requirements, whether an inactive USGS station existed, and available streamflow data. A majority of the sites are known to be accessible with landowner permission, and some sites may require helicopter transport (See the “Data-Quality Objectives, Surface Water, Proper Installation and Maintenance” section for detailed discussion on site selection).

Some active, continuous stations operated by USGS and CWRM are excluded from the monitoring program and these stations are summarized in table 10. These stations may have been established to meet needs not related to the monitoring needs for this assessment.

Issues related to surface-water resource management and climate change were identified during stakeholder workshops. These issues, summarized in the “Current Surface-Water Resource Issues” section, were used to develop criteria for evaluating individual monitoring stations within the current surface-water resource-monitoring program and additional monitoring stations identified for inclusion in the monitoring program. The monitoring stations were grouped into either or both the resource-management network and climate-response network.

Streams affected by groundwater withdrawal were considered for additional monitoring in both data-collection networks. Withdrawing water from aquifers near streams can reduce available surface-water resources by reducing groundwater discharge to the streams. Withdrawing water from many wells distributed over a large area may affect available surface-water resources on a regional scale. Therefore, flow in streams in some hydrogeologic settings near points of groundwater withdrawal need to be monitored to determine effects of the withdrawal.

## Resource-Management Network

Streamflow monitoring as a part of the resource-management network depends, in part, on whether a stream lies within a surface-water priority area. Surface-water priority areas were identified by CWRM and other stakeholders during stakeholder workshops. Area boundaries were delineated using CWRM’s surface-water hydrologic units (State of Hawai‘i, 2019c, p. 119–168). Surface-water priority areas generally included surface-water management areas, streams with interim instream-flow standards amended from status quo (table 8), streams with diversions contributing to large agricultural irrigation systems and hydropower development that are currently operational, and streams that support water leases.

Some streams have amended interim instream-flow standards requiring full restoration of streamflow to natural, undiverted conditions (table 8). In these cases, the communities must self-regulate the use of stream-water resources to ensure adequate stream flows for supporting stream life. Monitoring stations were not selected for streams with full restoration to economize available resources for streams with active diversions. Issuance of water leases to use public water resources requires information on the quantity of water being diverted. Since monitoring flow at all diversion intakes is costly, monitoring stations were selected in the affected streams to provide water-availability information. Water users may need to self-monitor using DLNR-approved means and report water usage to the CWRM.

A GIS dataset containing surface-water ditch systems, surface-water diversions registered with the CWRM, estimated withdrawal amounts at each diversion (if provided), and the operational status of each diversion—active, inactive, abandoned, and unknown—was obtained from CWRM and used as baseline information. Knowledge from USGS personnel gathered from previous surface-water investigations and conversations with various landowners was used to verify the current operational status of some of the diversions with “unknown” status.

Streams that support fish and wildlife habitat as indicated in the Hawai‘i Division of Aquatic Resources freshwater database (State of Hawai‘i, 2008a) and streams that support traditional and cultural practices as indicated in Hawai‘i Stream Assessment (State of Hawai‘i, 1990) were given higher priority for additional monitoring. Most of these streams lie within a surface-water priority area, and additional monitoring stations are needed to determine adequate streamflow for supporting stream life downstream from diversions.

Streams in areas with limited or no existing hydrologic data were selected for additional monitoring to address the lack of hydrologic information for instream-flow standard development. In each of these areas, the occasional intensive monitoring data-collection strategy is appropriate; concurrent operation of a newly established continuous low-flow station and several partial-record stations can be used to describe the hydrologic characteristics for each region. Following an appropriate and representative monitoring-period length, the decision to discontinue the monitoring stations depends on the statistical correlations between the discharges at the continuous station and partial-record stations. A station may be discontinued if the data from the station are appropriately correlated with data from active continuous stations. Partial-record stations may be discontinued if the discrete data are correlated with data at the continuous station. Some partial-record stations can be converted to continuous stations because the flow data do not correlate with data from any active continuous stations.

### Kaua‘i

All of the stations selected for the monitoring program for Kaua‘i—22 continuous stations and 8 partial-record stations—are part of the resource-management network (fig. 11, table 11). A majority of the stations are selected for streams in priority areas to quantify water availability for agriculture, native species habitat protection, hydropower production, and to develop instream-flow standards. Wainiha River (C2, C3; fig. 11, table 11, map identification number in the figure and table corresponding to the island in discussion) supports the first hydropower facility built in Hawai‘i, and the facility has the largest annual power production on the island (Wilcox, 1996, p. 79; Kaua‘i Island Utility Cooperative [KIUC], 2017, p. 15). Hanalei River (C4) is important for native waterfowl habitat protection and wetland-taro irrigation at the Hanalei

**Table 10.** Continuous-record streamflow-gaging stations, in operation in 2018, not selected for the surface-water resource-monitoring program for Hawai‘i.

[CWRM, State of Hawai‘i Commission on Water Resource Management; HI, Hawaii; N, North; nr, near; P, present (2019); Quar., Quarantine; SF, South Fork; Stn, Station; Str, Stream; USGS, U.S. Geological Survey]

| Island | Operating agency | Station ID | Station name[1] | Altitude,[2] in feet | Latitude[3] | Longitude[3] | Aspect | Period of record | Years of record[4] | Flow classification |
|---|---|---|---|---|---|---|---|---|---|---|
| Kaua‘i | USGS | 16060000 | SF Wailua River nr Lihue, Kauai, HI | 240 | 22.037 | −159.380 | Windward | 1912–P | 101 | Regulated |
| O‘ahu | USGS | 16226400 | N. Halawa Str nr Quar. Stn. at Halawa, Oahu, HI | 60 | 21.372 | −157.913 | Leeward | 2001–03, 2005–P | 15 | Natural |
| O‘ahu | USGS | 16241600 | Manoa Stream at Woodlawn Drive, Oahu, HI | 130 | 21.308 | −157.810 | Leeward | 2011–P | 6 | Natural |
| O‘ahu | USGS | 16249000 | Waimanalo Str at Waimanalo, Oahu, HI | 20 | 21.350 | −157.729 | Windward | 1967–70, 2015–P | 5 | Regulated |
| Moloka‘i | USGS | 16414200 | Kaunakakai Gulch at altitude 75 feet, Molokai, HI | 80 | 21.097 | −157.018 | Leeward | 2003–P | 15 | Regulated |
| Maui | CWRM | 6-158 | Honolua Stream at mouth | 20 | 21.013 | −156.632 | Windward | 2017–P | 1 | Regulated |
| Maui | CWRM | 6-155 | Wahikuli Gulch at mouth | 5 | 20.913 | −156.689 | Leeward | P | 0 | Regulated |
| Maui | CWRM | 6-62 | Wailuanui Stream above Hana Highway | 680 | 20.832 | −156.138 | Windward | 2015–P | 3 | Natural beginning 6/2018 |
| Maui | CWRM | 6-64 | Waiohue Stream near Hana Highway | 1,200 | 20.817 | −156.125 | Windward | 2015–P | 3 | Natural beginning 6/2018 |
| Maui | CWRM | 6-65 | West Wailuaiki Stream near Hana Highway | 1,180 | 20.822 | −156.138 | Windward | 2015–P | 3 | Natural beginning 6/2018 |
| Maui | CWRM | 6-123 | Kahoma Stream below diversion | 530 | 20.896 | −156.659 | Windward | 2017–P | 1 | Regulated |

[1]NWIS and CWRM database limitations preclude the use of Hawaiian diacritical marks in USGS station names.

[2]Altitude values interpolated from USGS 1:24,000-scale digital hypsography data and rounded to the nearest ten.

[3]Latitude and longitude coordinates in North American Datum of 1983.

[4] Number of years of complete continuous record as of the end of 2018 water year. A water year is a 12-month period that extends from October 1 to September 30 of the following year and is named according to the year during which the period ends.

National Wildlife Refuge (State of Hawai‘i, 2016b, p. 53). Major surface-water diversions do not currently exist for Moloa‘a Stream (P3); however, the State has indicated potential uses in the area that warrant monitoring of streamflow. Keālia and Kapa‘a Streams (C6, C7) provide irrigation water for diversified agriculture and pasture management occurring in the eastern coastal areas of the island. Wailuā River, Hulē‘ia Stream, and their tributary streams (C10–C14) are diverted by several interconnected ditches that supply irrigation water for seed production, commercial forestry, pasture management, and diversified crops. Water diverted from Waiahi Stream (C12), a tributary of Wailuā River, supports two hydropower facilities in the valley. Lāwa‘i Stream (C15, C16) supplies irrigation water for coffee cultivated near the south shore. Hanapēpē River, Olokele River, and Makaweli River (C17, P4, C18) provide irrigation water mainly for seed production and pasture management in the western coastal areas (State of Hawai‘i, 2016b, p. 50). Olokele River also supports a hydropower facility, and a larger hydropower expansion facility is currently being constructed below the existing facility (KIUC, 2017, p. 15; D’Angelo, 2014). The tributaries of Waimea River (C19–C22, P5) are diverted to provide water for pasture management, livestock, taro cultivation, and recreational uses in the western part of the island. Diverted flow from Waimea River also supports two hydropower facilities in the area (State of Hawai‘i, 2016a, p. ES-1–3), and a pumped-storage hydropower facility is currently under development (State of Hawai‘i, 2018b). Monitoring stations on Wai‘oli (P2), Moloa‘a (P3), and Koai‘e (P5) Streams were established as part of a separate ongoing statewide surface-water availability study (hereafter referred as “2018 statewide low-flow study”) to monitor low-flow conditions during 2018–2021.

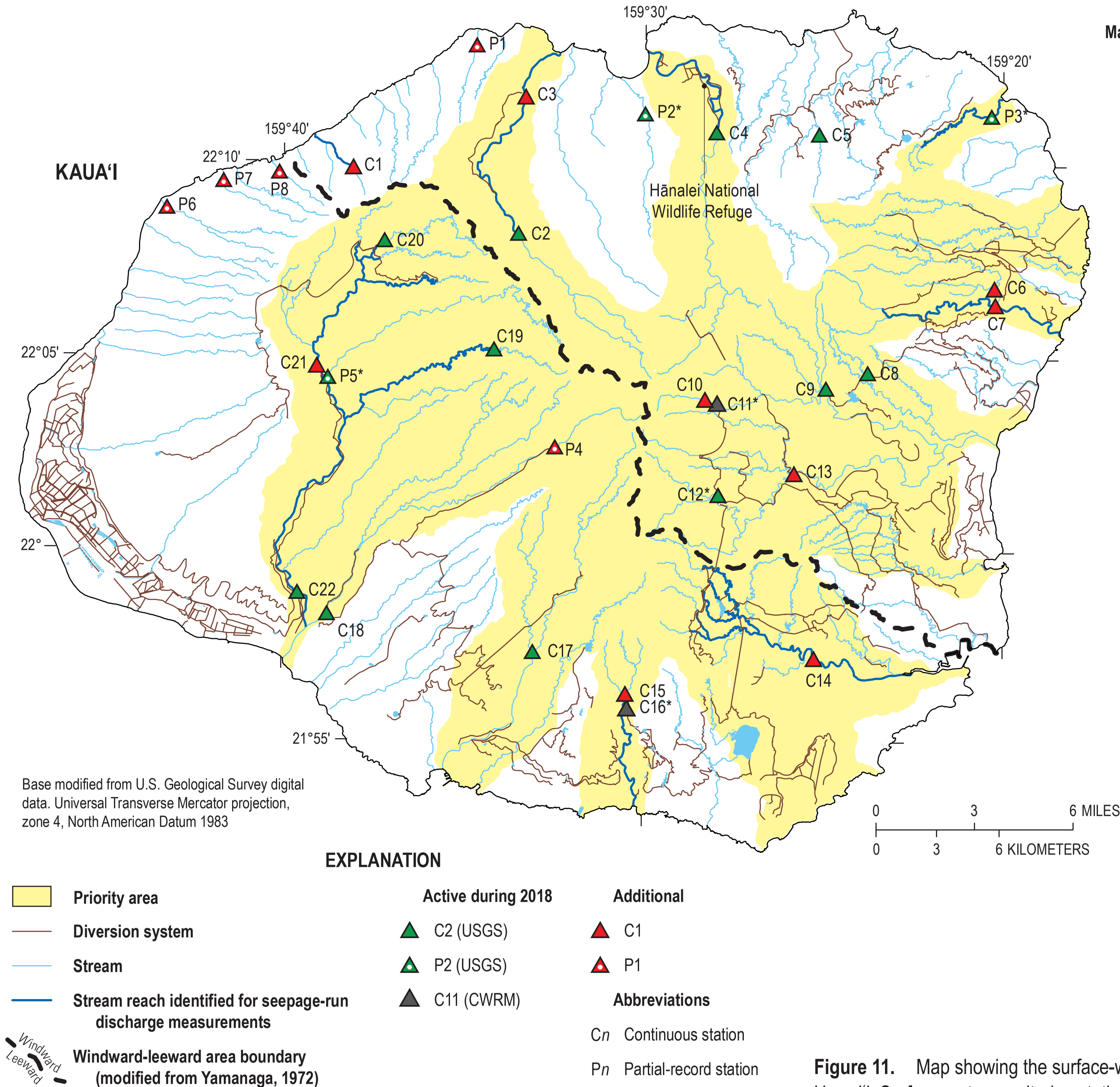
Data from active continuous stations on Wainiha River (C2), Hanalei River (C4), ‘Ōpaeka‘a Stream (C8), east branch of North Fork Wailuā River (C9), Wai‘alae Stream (C19), and Kawaikōī Stream (C20) have been shown to correlate well with data from partial-record stations on the island; therefore, the continuous stations are included in the network as index stations. Active continuous station 16060000 on South Fork Wailuā River (located about 4.6 mi downstream from C13) is excluded from the monitoring program because it is located downstream from a ditch-return flow and therefore does not capture effects of surface-water diversion on streamflow immediately downstream from the diversion intake. Instead, continuous station C13 is selected for monitoring diverted-flow conditions on South Fork Wailuā River for instream-flow standard regulation.

Seven stations are selected for monitoring streams in non-priority areas. Hydrologic information in the northeast coast of Kaua‘i is scarce, and concurrent operation of stations C1, P1, P6–P8 is for describing streamflow characteristics in this area. Monitoring is identified for Wai‘oli Stream (P2) because it currently provides irrigation water for taro cultivation and small vegetable farms in the valley. The long-term continuous station on Hālaulani Stream (C5) is a needed index station.

### O‘ahu

The resource-management network of the monitoring program for O‘ahu is represented by 36 continuous stations and 12 partial-record stations (fig. 12, table 12). Surface-water priority areas consist of drainage basins of Punalu‘u, Kahana, Waikāne, Waiāhole, Kawainui, Waimānalo, Waikele, Kaukonahua, and Kaupuni Streams. Flow from Punalu‘u Stream (C3, C4; fig. 12, table 12) supports mainly diversified agriculture, aquaculture, and wetland-taro cultivation within the stream valley. Kahana Stream (C5) is the only surface-water source contributing to irrigation needs in the central plains through the Waiāhole Ditch System, which conveys mostly high-level dike-impounded groundwater originating mainly from Kahana (C5), Waikāne (C6), and Waiāhole (C7) Stream basins. Tributaries of Kawainui Stream (C13–C15) provide irrigation water for landscaping and diversified agriculture in the subdivision within the valley. Concurrent operation of stations C14 and C16 is identified because the combined record from these two stations provides an estimate of total natural streamflow flowing past station C14. Kaukonahua Stream (C33, C39) and its tributaries (C30, C31), Poamoho Stream (P9), and Helemano Stream (P10) provide irrigation water for pineapple and diversified crops cultivated in the northwestern part of the island (Honolulu Board of Water Supply [HBWS], 2016, p. 3-20). Wahiawā Reservoir (Lake Wilson), part of the Wahiawā Irrigation System (C32), is one of the largest reservoirs in the State, and it is being considered for hydropower production (Daysog, 2017). Kaupuni Stream (C35) and its tributary (C34) may be affected by groundwater withdrawal, and HBWS is continuing to reduce withdrawal in an effort to restore natural flow in the stream (HBWS, 2009, p. ES-12).

More than half of the island contains non-priority areas where streams have active continuous stations (C2, C8–C11, C20–C23, C25–C29, C36, C37, C41) included in the monitoring program for instream-flow standard development and enforcement. Monitoring stations on Waihe‘e (C8), Kahalu‘u (C9), He‘eia (C10), Kāne‘ohe (C11), Luluku (P4), and Mākaha (C36) Streams are intended to determine potential effects of groundwater withdrawal to streamflow. These streams are affected by groundwater withdrawal through water-development tunnels and (or) wells near streams (Takasaki and others, 1969; HBWS, 2009). The northern part of the island has limited unregulated-flow data, and monitoring stations P1–P3, C1 (inactive continuous station on Mālaekahana Stream), and C40 (conversion of active crest-stage station to a continuous streamflow-gaging station) are needed to fill that data gap. Additional monitoring is identified for Kamo‘oali‘i Stream (P5) because historical measurements indicated poor correlations with data from active continuous stations available at the time. Partial-record stations on Wailupe Gulch (P6), Waimano Stream (P7), and Nānākuli Stream (P8) are needed because of limited hydrologic data. Tributaries of Kawailoa Gulch—Kawai‘iki (P11) and Kawainui (P12) Streams—support agriculture in the northern part of the island. Stations P11 and P12 are intended to estimate surface-water availability upstream from the diversions, and station C38 is selected for instream-flow standard development and enforcement.




**Map identification number index**—Stream name (N, natural flow or R, regulated flow); "+" indicates reactivation of an inactive USGS station. For map identification number: "*" indicates station monitors low-flow conditions only

| | |
|---|---|
| C1 | Kalalau Stream (N) |
| C2 | Wainiha River (N) |
| C3 | Wainiha River (R) + |
| C4 | Hanalei River (N) |
| C5 | Hālaulani Stream (N) |
| C6 | Keālia Stream (R) |
| C7 | Kapa'a Stream (R) + |
| C8 | 'Ōpaeka'a Stream (N) |
| C9 | East branch of North Fork Wailuā River (N) |
| C10 | North Fork Wailuā River (N) |
| C11* | North Fork Wailuā River (R) |
| C12* | Waiahi Stream (N) |
| C13 | South Fork Wailuā River (R) |
| C14 | Hulē'ia Stream (R) + |
| C15 | Lāwa'i Stream (N) + |
| C16* | Lāwa'i Stream (R) |
| C17 | Hanapēpē River (R) |
| C18 | Makaweli River (R) |
| C19 | Wai'alae Stream (N) |
| C20 | Kawaikōī Stream (N) |
| C21 | Waimea River (R) + |
| C22 | Waimea River (R) |
| P1 | Limahuli Stream (N) + |
| P2* | Wai'oli Stream (N) |
| P3* | Moloa'a Stream (N) |
| P4 | Olokele River (N) + |
| P5* | Koai'e Stream (N) |
| P6 | Miloli'i Stream (N) + |
| P7 | Nu'alolo Stream (N) |
| P8 | Honopū Stream (N) |

**Figure 11.** Map showing the surface-water monitoring program on Kaua'i, Hawai'i. Surface-water monitoring stations are listed with their map identification number. Operating agencies include the U.S. Geological Survey (USGS) and the State of Hawai'i Commission on Water Resource Management (CWRM).

**Table 11.** Continuous-record streamflow-gaging stations and partial-record stations in the surface-water monitoring program for Kauaʻi, Hawaiʻi.

[alt, altitude; blw, below; conf, confluence; CWRM, State of Hawaiʻi Commission on Water Resource Management; EB, east branch; ft, feet; HI, Hawaii; LF, low flow; mi, mile; na, not applicable; NF, North Fork; nr, near; P, present (2018); RB, right branch; Riv, River; Str, Stream; US, upstream; USGS, U.S. Geological Survey; w, with]

| Map ID[1] | Status[2] | Operating agency | Station number[3] | Station name[4] or description[5] | Altitude,[6] in feet | Latitude[7] | Longitude[7] | Aspect | Period of record | Years of record[8] | Flow classification | Network[10] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Continuous stations | | | | | | | | | | | | |
| C1 | N | na | 16117000 | Kalalau Stream near Hanalei, Kauai, HI | 960 | 22.165 | −159.634 | Windward | 1931–55 | 22 | Natural | C W |
| C2 | A | USGS | 16108000 | Wainiha River nr Hanalei, Kauai, HI | 960 | 22.136 | −159.558 | Windward | 1952–P | 62 | Natural | C W |
| C3 | N | na | 16113000 | Wainiha River nr Wainiha, Kauai, HI | 70 | 22.195 | −159.554 | Windward | no data | 0 | Regulated | W |
| C4 | A | USGS | 16103000 | Hanalei River nr Hanalei, Kauai, HI | 60 | 22.180 | −159.466 | Windward | 1912–19, 1963–P | 61 | Natural beginning 1995 | C W |
| C5 | A | USGS | 16097500 | Halaulani Str at alt 400 ft nr Kilauea, Kauai, HI | 390 | 22.179 | −159.419 | Windward | 1957–P | 60 | Natural | C W |
| C6 | N | na | na | Keālia Stream downstream confluence with Mimino Stream | 120 | 22.112 | −159.337 | Windward | na | na | Regulated | W |
| C7 | N | na | 220619159201201 | Kapaa Str 300ft US conf w Kealia Str, Kauai, HI | 40 | 22.105 | −159.337 | Windward | 1983 | 1[9] | Regulated | W |
| C8 | A | USGS | 16071500 | Left Branch Opaekaa Str nr Kapaa, Kauai, HI | 460 | 22.076 | −159.396 | Windward | 1960–P | 58 | Natural | C W |
| C9 | A | USGS | 16068000 | EB of NF Wailua River nr Lihue, Kauai, HI | 500 | 22.069 | −159.415 | Windward | 1912–P | 103 | Natural | C W |
| C10 | N | na | na | North Fork Wailua River upstream Bluehole Intake | 1,100 | 22.063 | −159.468 | Windward | na | na | Natural | W |
| C11 | A | CWRM | 2-191 | North Fork Wailua River below Bluehole Intake | 1,070 | 20.062 | −159.466 | Windward | P (LF only) | 0 | Regulated | W |
| C12 | A | USGS | 16057900 | Waiahi Str US Upper Powerhouse, Kauai, HI | 820 | 22.023 | −159.465 | Windward | 2015–P (LF only) | 2 | Natural | C W |
| C13 | N | na | na | South Fork Wailua River downstream Hanamaulu Ditch | 430 | 22.032 | −159.430 | Windward | na | na | Regulated | W |
| C14 | N | na | 16055000 | Huleia Str nr Lihue, Kauai, HI | 240 | 21.953 | −159.420 | Leeward | 1912–1915, 1967–1970 | 6 | Regulated | W |

**Table 11.** Continuous-record streamflow-gaging stations and partial-record stations in the surface-water monitoring program for Kauaʻi, Hawaiʻi.—Continued

| Map ID[1] | Status[2] | Operating agency | Station number[3] | Station name[4] or description[5] | Altitude,[6] in feet | Latitude[7] | Longitude[7] | Aspect | Period of record | Years of record[8] | Flow classification | Network[10] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Continuous stations—Continued | | | | | | | | | | | | |
| C15 | N | na | 16052400 | RB Lawai Stream 300ft US of fork, Kauai, HI | 600 | 21.937 | −159.508 | Leeward | 2016–P (LF only) | 2 | Natural | C W |
| C16 | A | CWRM | 2-194 | Lawai Stream below Lawai Ditch | 520 | 21.931 | −159.507 | Leeward | P (LF only) | 0 | Regulated | W |
| C17 | A | USGS | 16049000 | Hanapepe Riv blw Manuahi Str nr Eleele, Kauai, HI | 220 | 21.955 | −159.551 | Leeward | 1917–21, 1926–P | 94 | Regulated | W |
| C18 | A | USGS | 16036000 | Makaweli River nr Waimea, Kauai, HI | 20 | 21.971 | −159.646 | Leeward | 1943–P | 75 | Regulated | W |
| C19 | A | USGS | 16019000 | Waialae Str at alt 3,820 ft nr Waimea, Kauai, HI | 3,820 | 22.086 | −159.569 | Leeward | 1920–32, 1952–P | 76 | Natural | C W |
| C20 | A | USGS | 16010000 | Kawaikoi Stream nr Waimea, Kauai, HI | 3,420 | 22.133 | −159.620 | Leeward | 1909–16, 1919–P | 101 | Natural | C W |
| C21 | N | na | 16016000 | Waimea River abv Kekaha-Waiahulu Intake, Kauai, HI | 790 | 22.079 | −159.651 | Leeward | 1916, 1917–18, 1925–68 | 39 | Regulated | W |
| C22 | A | USGS | 16031000 | Waimea River near Waimea, Kauai, HI | 20 | 21.980 | −159.660 | Leeward | 1910–19, 1943–72, 1975–97, 2016–P | 55 | Regulated | W |
| Partial-record stations | | | | | | | | | | | | |
| P1 | N | na | 16114000 | Limahuli Str nr Wainiha, Kauai, HI | 200 | 22.218 | −159.577 | Windward | 1994–2005 | 7 | Natural | W |
| P2 | A | USGS | 221118159295701 | Waioli Stream 1.5 mi US str mouth, Kauai, HI | 40 | 22.188 | −159.499 | Windward | Station established in 2018 | na | Natural | W |
| P3 | A | USGS | 221111159203401 | Moloaa Stream at Koolau Rd, Kauai, HI | 70 | 22.187 | −159.343 | Windward | Station established in 2018 | na | Natural | W |
| P4 | N | na | 16034000 | Olokele River nr Waimea, Kauai, HI | 1,500 | 22.043 | −159.542 | Leeward | na | na | Natural | W |
| P5 | A | USGS | 220427159384501 | Koaie Str US Kekaha Ditch intake, Kauai, HI | 780 | 22.074 | −159.646 | Leeward | Station established in 2018 | na | Natural | W |
| P6 | N | na | 220851159431501 | Milolii Str .21mi US mouth, Kauai, HI | 110 | 22.148 | −159.721 | Leeward | 1947–50 | 9[9] | Natural | W |

**Table 11.** Continuous-record streamflow-gaging stations and partial-record stations in the surface-water monitoring program for Kauaʻi, Hawaiʻi.—Continued

| Map ID[1] | Status[2] | Operating agency | Station number[3] | Station name[4] or description[5] | Altitude,[6] in feet | Latitude[7] | Longitude[7] | Aspect | Period of record | Years of record[8] | Flow classification | Network[10] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Partial-record stations—Continued | | | | | | | | | | | | |
| P7 | N | na | na | Nualolo Stream near mouth | 200 | 22.159 | −159.695 | Leeward | na | na | Natural | W |
| P8 | N | na | na | Honopu Stream near mouth | 360 | 22.163 | −159.669 | Leeward | na | na | Natural | W |

[1]Map identification number illustrated in figure 11.

[2]Status of "A" represents an active station as of 2018. Status of "N" represents an additional station needed to supplement the current (2018) program.

[3]Station with a status of "N" that is not a reactivation of an inactive USGS station does not have a station number.

[4]NWIS and CWRM database limitations preclude the use of Hawaiian diacritical marks in station names.

[5]Station with a status of "N" that is not a reactivation of an inactive USGS station does not have a station name; instead, a station description is provided.

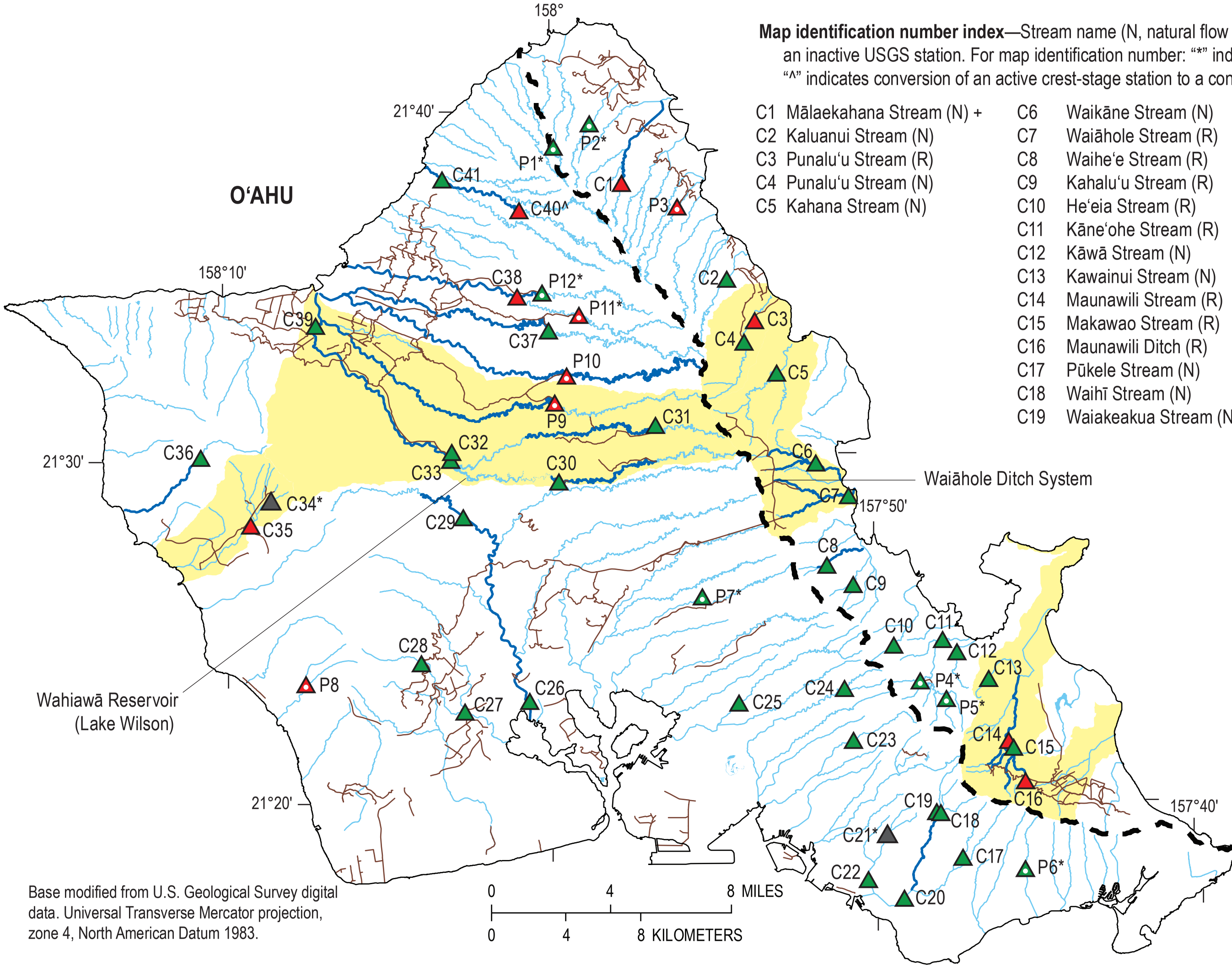
[6]Altitude values interpolated from USGS 1:24,000-scale digital hypsography data and rounded to the nearest ten.

[7]Latitude and longitude coordinates in North American Datum of 1983.

[8]For USGS stations, number of years of complete continuous record as of the end of 2018 water year. A water year is a 12-month period that extends from October 1 to September 30 of the following year and is named according to the year during which the period ends. For CWRM stations, an estimate of the number of years of continuous record as of the end of 2018 water year is included.

[9]Number of measurements within the indicated period of record as of May 2019.

[10]A station can be in one or both of the following networks: "C" represents Climate-Response Network. "W" represents Water-Management Network.




Base modified from U.S. Geological Survey digital data. Universal Transverse Mercator projection, zone 4, North American Datum 1983.

**Map identification number index**—Stream name (N, natural flow or R, regulated flow); "+" indicates reactivation of an inactive USGS station. For map identification number: "*" indicates station monitors low-flow conditions only; "^" indicates conversion of an active crest-stage station to a continuous station

| | |
|---|---|
| C1 | Mālaekahana Stream (N) + |
| C2 | Kaluanui Stream (N) |
| C3 | Punalu‘u Stream (R) |
| C4 | Punalu‘u Stream (N) |
| C5 | Kahana Stream (N) |
| C6 | Waikāne Stream (N) |
| C7 | Waiāhole Stream (R) |
| C8 | Waihe‘e Stream (R) |
| C9 | Kahalu‘u Stream (R) |
| C10 | He‘eia Stream (R) |
| C11 | Kāne‘ohe Stream (R) |
| C12 | Kāwā Stream (N) |
| C13 | Kawainui Stream (N) |
| C14 | Maunawili Stream (R) |
| C15 | Makawao Stream (R) |
| C16 | Maunawili Ditch (R) |
| C17 | Pūkele Stream (N) |
| C18 | Waihī Stream (N) |
| C19 | Waiakeakua Stream (N) |
| C20 | Mānoa Pālolo Drainage Canal (R) |
| C21* | Makiki Stream (N) |
| C22 | Makiki Stream (R) |
| C23 | Kalihi Stream (N) |
| C24 | Moanalua Stream (N) |
| C25 | North Hālawa Stream (N) |
| C26 | Waikele Stream (R) |
| C27 | Honouliuli Stream (R) |
| C28 | Honouliuli Stream Tributary (N) |
| C29 | Waikele Stream (N) |
| C30 | South Fork Kaukonahua Stream (N) |
| C31 | North Fork Kaukonahua Stream (N) |
| C32 | Wahiawa Ditch (R) |
| C33 | Kaukonahua Stream (R) |
| C34* | Kānewai Stream (R) |
| C35 | Kaupuni Stream (R) + |
| C36 | Mākaha Stream (R) |
| C37 | ‘Ōpae‘ula Stream (N) |
| C38 | Kawailoa Gulch (R) |
| C39 | Kaukonahua Stream (R) |
| C40^ | Kamananui Stream (N) |
| C41 | Kamananui Stream (R) |
| P1* | ‘Ō‘io Gulch (N) |
| P2* | ‘Ōhi‘a‘ai Gulch (N) |
| P3 | Kōloa Gulch (N) + |
| P4* | Luluku Stream (R) |
| P5* | Kamo‘oali‘i Stream (N) |
| P6* | Wailupe Gulch (N) |
| P7* | Waimano Stream (N) |
| P8 | Nānākuli Stream (N) |
| P9 | Poamoho Stream (N) + |
| P10 | Helemano Stream (N) |
| P11* | Kawai‘iki Stream (N) |
| P12* | Kawainui Stream (N) |

**EXPLANATION**

- **Priority area**
- **Diversion system**
- **Stream**
- **Stream reach identified for seepage-run discharge measurements**
- **Windward-leeward area boundary (modified from Yamanaga, 1972)** — Windward / Leeward

| **Active during 2018** | **Additional** |
|---|---|
| C2 (USGS) | C1 |
| P1 (USGS) | P3 |
| C21 (CWRM) | |

**Abbreviations**

*Cn* Continuous station

*Pn* Partial-record station

**Figure 12.** Map showing the surface-water monitoring program on O‘ahu, Hawai‘i. Surface-water monitoring stations are listed with their map identification number. Operating agencies include the U.S. Geological Survey (USGS) and the State of Hawai‘i Commission on Water Resource Management (CWRM).

**Table 12.** Continuous-record streamflow-gaging stations and partial-record stations in the surface-water monitoring program for O‘ahu, Hawai‘i.

[abv, above; alt, altitude; bl, below; blw, below; CWRM, State of Hawai‘i Commission on Water Resource Management; E, East; ft, feet; Gl, Gulch; HI, Hawaii; Hwy, Highway; N, North; na, not applicable; nr, near; P, present (2018); RB, Right Branch; Rd, Road; Res, Reservoir; St., Street; Str, Stream; trib, tributary; USGS, U.S. Geological Survey; U/S, upstream]

| Map ID[1] | Status[2] | Operating agency | Station number[3] | Station name[4] or description[5] | Altitude[6], in feet | Latitude[7] | Longitude[7] | Aspect | Period of record | Years of record[8] | Flow classification | Network[10] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Continuous stations | | | | | | | | | | | | |
| C1 | N | na | 16308990 | Malaekahana Stream nr Laie, Oahu, HI | 450 | 21.633 | −157.962 | Windward | 1963–71 | 7 | Natural | C W |
| C2 | A | USGS | 16304200 | Kaluanui Stream nr Punaluu, Oahu, HI | 110 | 21.586 | −157.908 | Windward | 1967–P | 51 | Natural | C W |
| C3 | N | na | na | Punaluu Stream at altitude 120 feet | 120 | 21.567 | −157.894 | Windward | na | na | Regulated | W |
| C4 | A | USGS | 16301050 | Punaluu Str abv Punaluu Ditch Intake, Oahu, HI | 210 | 21.556 | −157.899 | Windward | 1953–P | 63 | Natural | C W |
| C5 | A | USGS | 16296500 | Kahana Str at alt 30 ft nr Kahana, Oahu, HI | 30 | 21.541 | −157.882 | Windward | 1959–P | 57 | Natural beginning 7/2015 | C W |
| C6 | A | USGS | 16294900 | Waikane Str at alt 75 ft at Waikane, Oahu, HI | 80 | 21.497 | −157.863 | Windward | 1960–P | 56 | Natural beginning 7/2015 | C W |
| C7 | A | USGS | 16294100 | Waiahole Stream above Kamehameha Hwy, Oahu, HI | 10 | 21.482 | −157.846 | Windward | 2001–P | 15 | Regulated | W |
| C8 | A | USGS | 16284200 | Waihee Str nr Kahaluu, Oahu, HI | 170 | 21.448 | −157.857 | Windward | 1974–P | 44 | Regulated | W |
| C9 | A | USGS | 16283200 | Kahaluu Str nr Ahuimanu, Oahu, HI | 150 | 21.439 | −157.844 | Windward | 1983–P | 35 | Regulated | W |
| C10 | A | USGS | 16275000 | Heeia Stream at Haiku Valley nr Kaneohe, Oahu, HI | 270 | 21.409 | −157.823 | Windward | 1914–19, 1939–77, 1982–P | 78 | Regulated | W |
| C11 | A | USGS | 16274100 | Kaneohe Str blw Kamehameha Hwy, Oahu, HI | 30 | 21.412 | −157.798 | Windward | 2016–P | 2 | Regulated | W |
| C12 | A | USGS | 16265000 | Kawa Str at Kaneohe, Oahu, HI | 50 | 21.406 | −157.790 | Windward | 2016–P | 2 | Natural | C |
| C13 | A | USGS | 16264690 | Kawainui Stream near Kailua, Oahu, HI | 160 | 21.393 | −157.774 | Windward | 2016–P | 0 | Natural | W |
| C14 | N | na | na | Maunawili Stream 380 feet downstream Maunawili Road | 80 | 21.363 | −157.765 | Windward | na | na | Regulated | W |
| C15 | A | USGS | 16254000 | Makawao Str nr Kailua, Oahu, HI | 100 | 21.360 | −157.762 | Windward | 1912–16, 1958–2006, 2008–P | 58 | Regulated | W |

**Table 12.** Continuous-record streamflow-gaging stations and partial-record stations in the surface-water monitoring program for O‘ahu, Hawai‘i.—Continued

| Map ID[1] | Status[2] | Operating agency | Station number[3] | Station name[4] or description[5] | Altitude[6], in feet | Latitude[7] | Longitude[7] | Aspect | Period of record | Years of record[8] | Flow classification | Network[10] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Continuous stations——Continued | | | | | | | | | | | | |
| C16 | N | na | na | Maunawili Ditch at Makawao Stream | 410 | 21.343 | −157.756 | Windward | na | na | Regulated | W |
| C17 | A | USGS | 16244000 | Pukele Stream near Honolulu, Oahu, HI | 340 | 21.307 | −157.788 | Leeward | 1926–82, 2002–05, 2010–P | 66 | Natural | C |
| C18 | A | USGS | 16238500 | Waihi Stream at Honolulu, Oahu, HI | 290 | 21.328 | −157.801 | Leeward | 1913–21, 1925–83, 2011–P | 71 | Natural beginning 1983 | C |
| C19 | A | USGS | 16240500 | Waiakeakua Str at Honolulu, Oahu, HI | 290 | 21.328 | −157.800 | Leeward | 1913–20, 1925–P | 100 | Natural | C |
| C20 | A | USGS | 16247100 | Manoa-Palolo Drainage Canal at Moiliili, Oahu, HI | 5 | 21.286 | −157.818 | Leeward | 1999–P | 18 | Regulated | W |
| C21 | A | CWRM | 3-115 | Makiki Stream at 400 feet | 400 | 21.318 | −157.827 | Leeward | 2016–P | 1 | Natural | W |
| C22 | A | USGS | 16238000 | Makiki Stream at King St. bridge, Oahu, HI | 10 | 21.297 | −157.837 | Leeward | 2010–P | 7 | Regulated | W |
| C23 | A | USGS | 16229000 | Kalihi Str nr Honolulu, Oahu, HI | 460 | 21.363 | −157.844 | Leeward | 1913–P | 104 | Natural | C W |
| C24 | A | USGS | 16227500 | Moanalua Stream nr Kaneohe, Oahu, HI | 690 | 21.388 | −157.849 | Leeward | 1968–78, 2013–P | 14 | Natural | C |
| C25 | A | USGS | 16226200 | N. Halawa Str nr Honolulu, Oahu, HI | 160 | 21.382 | −157.903 | Leeward | 1983–P | 35 | Natural | C W |
| C26 | A | USGS | 16213000 | Waikele Str at Waipahu, Oahu, HI | 1 | 21.383 | −158.011 | Leeward | 1951–P | 64 | Regulated | W |
| C27 | A | USGS | 16212490 | Honouliuli Str at H-1 Freeway nr Waipahu, Oahu, HI | 140 | 21.378 | −158.045 | Leeward | 2012–P | 5 | Regulated | W |
| C28 | A | USGS | 16212480 | Honouliuli Stream Tributary near Waipahu, Oahu, HI | 630 | 21.402 | −158.067 | Leeward | 2012–P | 6 | Natural | C W |
| C29 | A | USGS | 16212601 | Waikele Str at Wheeler Field, Oahu, HI | 710 | 21.472 | −158.044 | Leeward | 2007–10, P | 3 | Natural | C W |
| C30 | A | USGS | 16208000 | SF Kaukonahua Str at E pump, nr Wahiawa, Oahu, HI | 860 | 21.489 | −157.996 | Leeward | 1957–63, 1964–2011, 2013–P | 55 | Natural | C W |
| C31 | A | USGS | 16200000 | NF Kaukonahua Str abv RB, nr Wahiawa, Oahu, HI | 1,150 | 21.516 | −157.945 | Leeward | 1913–53, 1960–P | 95 | Natural | C W |
| C32 | A | USGS | 16210100 | Wahiawa Ditch at Wahiawa, Oahu, HI | 790 | 21.500 | −158.051 | Leeward | 2012–P | 6 | Regulated | W |

**Table 12.** Continuous-record streamflow-gaging stations and partial-record stations in the surface-water monitoring program for O‘ahu, Hawai‘i.—Continued

| Map ID[1] | Status[2] | Operating agency | Station number[3] | Station name[4] or description[5] | Altitude[6], in feet | Latitude[7] | Longitude[7] | Aspect | Period of record | Years of record[8] | Flow classification | Network[10] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Continuous stations—Continued | | | | | | | | | | | | |
| C33 | A | USGS | 16210200 | Kaukonahua Stream blw Wahiawa Reservoir, Oahu, HI | 760 | 21.500 | −158.051 | Leeward | 2013–P | 4 | Regulated | W |
| C34 | A | CWRM | 3-101 | Kanewai Stream at 1000 feet | 1,000 | 21.480 | −158.144 | Leeward | 2016–P | 2 | Regulated | W |
| C35 | N | na | 16211800 | Kaupuni Str at alt 374 ft nr Waianae, Oahu, HI | 370 | 21.469 | −158.154 | Leeward | 1960–72 | 12 | Regulated | W |
| C36 | A | USGS | 16211600 | Makaha Str nr Makaha, Oahu, HI | 940 | 21.501 | −158.180 | Leeward | 1959–P | 58 | Regulated | W |
| C37 | A | USGS | 16345000 | Opaeula Str nr Wahiawa, Oahu, HI | 1,120 | 21.562 | −158.000 | Leeward | 1959–P | 59 | Natural | C W |
| C38 | N | na | na | Kawailoa Gulch downstream confluence with Kawaiiki Stream | 600 | 21.579 | −158.016 | Leeward | na | na | Regulated | W |
| C39 | A | USGS | 16210500 | Kaukonahua Str at Waialua, Oahu, HI | 20 | 21.565 | −158.120 | Leeward | 2012–P | 6 | Regulated | W |
| C40 | N | USGS | 16325000 | Kamananui Str at Pupukea Mil Rd, Oahu, HI | 590 | 21.620 | −158.015 | Leeward | 1963–2001, 2013–P (stage only) | 38 | Natural | C W |
| C41 | A | USGS | 16330000 | Kamananui Str at Maunawai, Oahu, HI | 20 | 21.635 | −158.054 | Leeward | 1958–P | 60 | Regulated | W |
| Partial-record stations | | | | | | | | | | | | |
| P1 | A | USGS | 213846157594401 | Oio Str at Drum Rd lower crossing, Oahu, HI | 1,190 | 21.646 | −157.995 | Windward | 1945, 1965–66, P | 0[9] | Natural | W |
| P2 | A | USGS | 213943157584201 | Ohiaai Gl at Charlie Rd, Oahu, HI | 380 | 21.662 | −157.978 | Windward | Station established in 2018 | 0[9] | Natural | W |
| P3 | N | na | 16306000 | Koloa Gulch nr Laie, Oahu, HI | 500 | 21.622 | −157.933 | Windward | 1914–18 | 2 | Natural | W |
| P4 | A | USGS | 16270900 | Luluku Str at alt 220 ft nr Kaneohe, Oahu, HI | 220 | 21.392 | −157.809 | Windward | 1967–98, P | 17 | Regulated | W |
| P5 | A | USGS | 16265700 | Kamooalii Str at alt 200 ft nr Kaneohe, Oahu, HI | 200 | 21.383 | −157.796 | Windward | 1959, 1983, 1985–98, 2006, P | 107[9] | Natural | W |
| P6 | A | USGS | 211803157452101 | Wailupe Gulch, 650 ft U/S of debris dam, Oahu, HI | 270 | 21.301 | −157.756 | Leeward | 2008, P | 3[9] | Natural | W |

**Table 12.** Continuous-record streamflow-gaging stations and partial-record stations in the surface-water monitoring program for O‘ahu, Hawai‘i.—Continued

| Map ID[1] | Status[2] | Operating agency | Station number[3] | Station name[4] or description[5] | Altitude[6], in feet | Latitude[7] | Longitude[7] | Aspect | Period of record | Years of record[8] | Flow classification | Network[10] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Partial-record stations—Continued | | | | | | | | | | | | |
| P7 | A | USGS | 212559159551701 | Waimano Str N trib abv Waimano Falls, Oahu, HI | 560 | 21.433 | −157.922 | Leeward | P | 1[9] | Natural | W |
| P8 | N | na | na | Nanakuli Stream at tributary confluence | 200 | 21.392 | −158.126 | Leeward | na | na | Natural | W |
| P9 | N | na | 213139157594901 | Poamoho Str at alt 1100 ft, nr Wahiawa, Oahu, HI | 1,100 | 21.527 | −157.997 | Leeward | 2006 | 1[9] | Natural | W |
| P10 | N | na | na | Helemano Stream upstream Helemano Ditch intake | 1,060 | 21.540 | −157.991 | Leeward | na | na | Natural | W |
| P11 | N | na | na | Kawaiki Stream above Kawaiiki Ditch, Oahi, HI | 1,140 | 21.569 | −157.986 | Leeward | na | na | Natural | W |
| P12 | A | USGS | 16335000 | Kawainui Stream above Kamananui Ditch, Oahu, HI | 740 | 21.580 | −158.003 | Leeward | 1960–61, 1963, P | 5[9] | Natural | W |

[1]Map identification number illustrated in figure 12.

[2]Status of “A” represents an active station as of 2018. Status of “N” represents an additional station needed to supplement the current (2018) program.

[3]Station with a status of “N” that is not a reactivation of an inactive USGS station does not have a station number.

[4]NWIS and CWRM database limitations preclude the use of Hawaiian diacritical marks in station names.

[5]Station with a status of “N” that is not a reactivation of an inactive USGS station does not have a station name; instead, a station description is provided.

[6]Altitude values interpolated from USGS 1:24,000-scale digital hypsography data and rounded to the nearest ten.

[7]Latitude and longitude coordinates in North American Datum of 1983.

[8]For USGS stations, number of years of complete continuous record as of the end of 2018 water year. A water year is a 12-month period that extends from October 1 to September 30 of the following year and is named according to the year during which the period ends. For CWRM stations, an estimate of the number of years of continuous record as of the end of 2018 water year is included.

[9]Number of measurements within the indicated period of record as of May 2019.

[10]A station can be in one or both of the following networks: “C” represents Climate-Response Network. “W” represents Water-Management Network.

## Moloka‘i

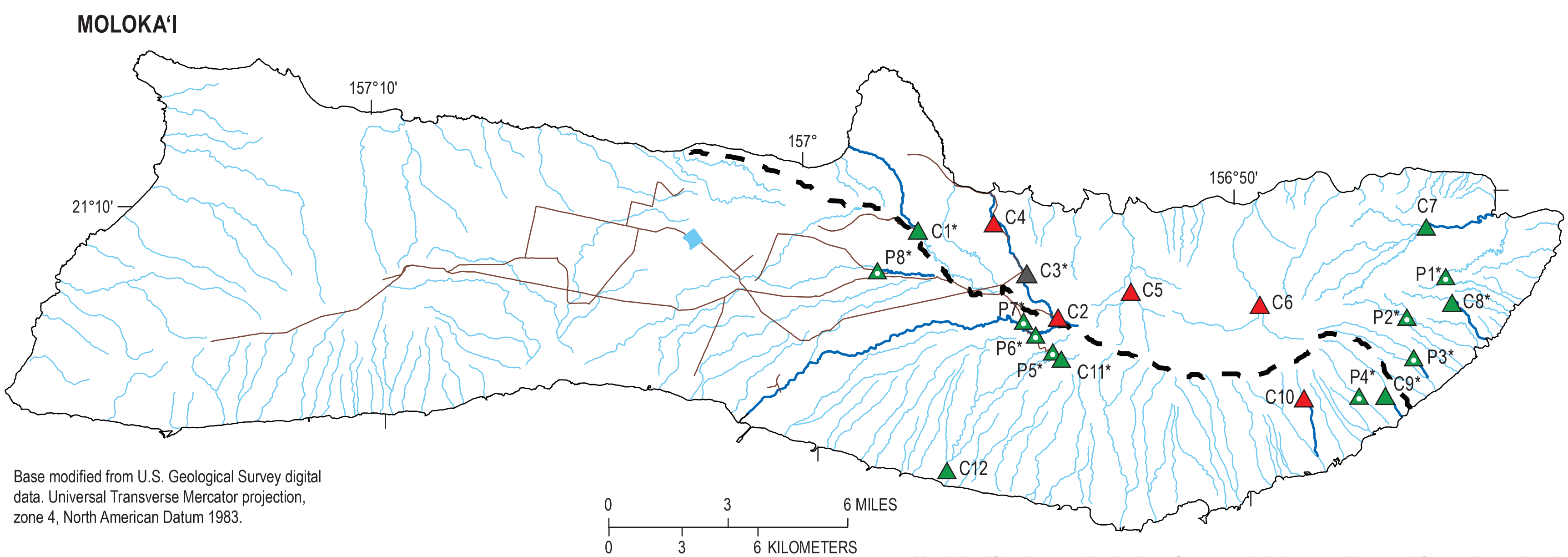
The resource-management network of the monitoring program for Moloka‘i is represented by 10 continuous stations and 8 partial-record stations (fig. 13, table 13). Surface-water priority areas consist of the drainage basins of Waikolu Stream, Kawela Gulch, and Kaunakakai Gulch. Waikolu Stream is an important source of irrigation water for the DHHL agricultural homestead in the northern central plateau (State of Hawai‘i, 2005, p. 7–3) and for diversified agriculture in the leeward (west) side of the island. The DHHL agricultural homestead is characterized as having some of the best agricultural lands in the State, and increased surface-water use is expected in the area (State of Hawai‘i, 2005). Three continuous stations (C2–C4; fig. 13, table 13) are selected for Waikolu Stream to monitor regulated-flow conditions resulting from multiple diversions. Combined flow records at stations C2 and C3 represent an estimate of total natural streamflow flowing past station C3 on Waikolu Stream, which assumes that any groundwater development in the diversion tunnel located within this reach does not affect the stream. The high-altitude reaches of Kawela Gulch support cattle operations in the leeward side of the island (State of Hawai‘i, 2016b, p. 66–67); therefore, continuous station C11 is intended to characterize water availability upstream from the diversion, and continuous station C12 is intended to monitor regulated-flow conditions. Monitoring stations in the upper reaches of Kawela and Kaunakakai Gulches (C11, P5–P7) were established as part of the 2018 statewide low-flow study.

A majority of the stations are in non-priority areas because existing hydrologic data are limited for the island and additional data are needed for establishing instream-flow standards. Long-term continuous station on Hālawa Stream (C7) is a needed index station because it is the only long-term continuous station on the island. Monitoring stations on Waihānau Stream (C1), Pāpio Gulch (P1), Honoulimalo‘o Stream (C8), Honouliwai Stream (P2), Waialua Stream (P3), Kainalu Gulch (C9), Honomuni Gulch (P4), and Kuhua‘awi Gulch (P8) within the non-priority areas were established as part of the 2018 statewide low-flow study. On the basis of the reconnaissance surveys conducted as part of the 2018 statewide low-flow study, Pāpio Gulch, Honoulimalo‘o, Honouliwai and Waialua Streams are currently diverted for uses within the respective basins. The monitoring station on Puna‘ula Gulch (C10) fills an important data gap for the leeward side of the island and is potentially a needed index station. Monitoring stations are not selected for the western part of the island because a majority of the streams flow only in direct response to rainfall.

## Maui

The resource-management network of the monitoring program for Maui is represented by 51 continuous streamflow-gaging stations, 1 ditch-flow-gaging station, and 12 partial-record stations. A majority of west Maui is a surface-water priority area, except for a few basins in the north and south, and monitoring stations are selected mainly for quantifying water availability for traditional and cultural uses, agriculture, domestic supply, hydropower production, and supporting instream-flow standard development (fig. 14, table 14). Honokōwai Stream (C1; fig. 14, table 14) provides irrigation water for coffee and nonpotable water supply for the subdivision in the area. Water diverted from the high-altitude reaches of Honokōhau Stream (C2–C4) is used mainly for irrigating diversified crops and golf courses, livestock, domestic water supply, and reforestation efforts. Waihe‘e River (C6, C7), Waiehu Stream (C8, P1, P2), Wailuku River (C9, C10), and Waikapū Stream (C11, P3), collectively known as Nā Wai ‘Ehā (“The Four Streams”), support cultural, irrigation, and public-supply water uses within the Nā Wai ‘Ehā area. Ukumehame Gulch (C12, C13), and Olowalu (C14), Launiupoko (C15), and Kaua‘ula (C16, C17) Streams provide for irrigation of small vegetable farms and landscape nurseries within the stream valleys (Cheng, 2014, p. 8; Maui County, 2017, p. 124–128). Kaua‘ula Stream also supports a small-scale hydropower facility in Lahaina, Hawai‘i (fig. 1). Kanahā Stream (C18) supports potable water use in the southwestern coastal areas of west Maui (Maui County, 2017, p. 78–79). Kahoma Stream (C19) supports ecotourism activities within the valley (Cheng, 2014, p. 8). An active crest-stage station on Kahoma Stream (C20) can be converted to a continuous streamflow-gaging station for monitoring diverted-flow conditions. Station C20 would replace a continuous station currently operated by CWRM on Kahoma Stream (table 10). Station C21 at the mouth of Wahikuli Gulch was established to support the West Maui Ridge to Reef Initiative in addressing adverse effects to coral reefs in west Maui (more information at https://www.westmauir2r.com/watershed-management-plans.html). Data from long-term active stations monitoring unregulated flow on Honokōhau Stream (C2) and Waihe‘e (C6) and Wailuku (C9) Rivers have been shown to correlate well with data from partial-record stations on the island, and the continuous stations are included in the network as index stations.

The northern part of east Maui is a surface-water priority area because a majority of the streams in the area support traditional and cultural practices, native aquatic habitat, agriculture, and domestic supply (fig. 15, table 14). Many streams require monitoring of established instream-flow standards and are part of several pending long-term water-lease applications (State of Hawai‘i, 2018c). In upcountry Maui, water from high-altitude reaches of Waikamoi (C32), Puohokamoa (C33), and Ha‘ipua‘ena (C34–C36) Streams support domestic use and irrigation needs in the area. The cessation of HC&S sugarcane-plantation operations has substantially decreased the amount of water diverted from east Maui streams to support irrigation needs in central Maui. According to CWRM water-use records as of May 2017, the amount of diverted water at two of the East Maui Irrigation (EMI) system main ditches decreased by more than 50 percent since January 2016, and some of the remaining ditches in the system have been dry or have had low flows. HC&S is required to cease all surface-water diversions on 10 streams in the priority area that the EMI system diverts (State of Hawai‘i, 2018a; 2018c). In order to shift available resources to monitor streams with active diversions, additional monitoring is not identified. Continuous stations (C23–C39, C42–C50)




Base modified from U.S. Geological Survey digital data. Universal Transverse Mercator projection, zone 4, North American Datum 1983.

**EXPLANATION**

- **Priority area**
- **Diversion system**
- **Stream**
- **Stream reach identified for seepage-run discharge measurements**
- Windward / Leeward — **Windward-leeward area boundary (modified from Yamanaga, 1972)**

**Active during 2018**

- C1 (USGS)
- P1 (USGS)
- C3 (CWRM)

**Additional**

- C2

**Abbreviations**

- C*n* Continuous station
- P*n* Partial-record station

**Map identification number index**—Stream and ditch name (N, natural flow or R, regulated flow); "+" indicates reactivation of an inactive USGS station. For map identification number: "*" indicates station monitors low-flow conditions only. Streamflow measured at stations C2 and C3 combined represents total natural flow in the stream flowing past C3

| | |
|---|---|
| C1* | Waihānau Stream (N) |
| C2 | Hanaliholiho Ditch (R) |
| C3* | Waikolu Stream (R) |
| C4 | Waikolu Stream (R) + |
| C5 | Pelekunu Stream (N) + |
| C6 | Pulena Stream (N) + |
| C7 | Hālawa Stream (N) |
| C8* | Honoulimaloʻo Stream (N) |
| C9* | Kainalu Gulch (N) |
| C10 | Punaʻula Gulch (N) + |
| C11* | East Fork Kawela Gulch (N) |
| C12 | Kawela Gulch (R) |
| P1* | Pāpio Gulch (N) |
| P2* | Honouliwai Stream (N) |
| P3* | Waialua Stream (N) |
| P4* | Honomuni Gulch (N) |
| P5* | West Fork Kawela Gulch (N) |
| P6* | Left Branch South Fork Kaunakakai Gulch (N) |
| P7* | Right Branch South Fork Kaunakakai Gulch (N) |
| P8* | Kuhuaʻawi Gulch (N) |

**Figure 13.** Map showing the surface-water monitoring program on Molokaʻi, Hawaiʻi. Surface-water monitoring stations are listed with their map identification number. Operating agencies include the U.S. Geological Survey (USGS) and the State of Hawaiʻi Commission on Water Resource Management (CWRM).

**Table 13.** Continuous-record streamflow-gaging stations and partial-record stations in the surface-water monitoring program for Moloka‘i, Hawai‘i.

[alt, altitude; bl, below; CWRM, State of Hawai‘i Commission on Water Resource Management; EF, east fork; ft, feet; Gl, gulch; HI, Hawaii; LB, left branch; LF, low flow; mi, mile; nr, near; P, present (2018); RB, right branch; SF, south fork; Str, Stream; US, upstream; USGS, U.S. Geological Survey; W, west]

| Map ID[1] | Status[2] | Operating agency | Station number[3] | Station name[4] or description[5] | Altitude,[6] in feet | Latitude[7] | Longitude[7] | Aspect | Period of record | Years of record[8] | Flow classification | Network[9] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Continuous stations | | | | | | | | | | | | |
| C1 | A | USGS | 16409000 | Waihanau Stream nr Kalaupapa, Molokai, HI | 2,250 | 21.157 | −156.958 | Windward | P (LF only) | 0 | Natural | C W |
| C2 | N | na | na | Hanaliholiho intake on Waikolu Stream | 3,810 | 21.125 | −156.905 | Windward | na | na | Regulated | W |
| C3 | A | CWRM | 4-125 | Waikolu Stream above Molokai Irrigation System intake | 1,090 | 21.139 | −156.918 | Windward | 2017–P | 1 | Regulated | W |
| C4 | N | na | 16408000 | Waikolu Str bl pipe cross nr Kalaupapa, Molokai, HI | 250 | 21.159 | −156.929 | Windward | 1919–32, 1937–96 | 68 | Regulated | W |
| C5 | N | USGS | 16404000 | Pelekunu Stream nr Pelekunu, Molokai, HI | 550 | 21.133 | −156.875 | Windward | 1919–28, 1937–57, 1971–82 | 36 | Natural | C |
| C6 | N | USGS | 16402000 | Pulena Stream near Wailau, Molokai, HI | 590 | 21.123 | −156.828 | Windward | 1919–28, 1937–57 | 27 | Natural | C |
| C7 | A | USGS | 16400000 | Halawa Stream near Halawa, Molokai, HI | 210 | 21.156 | −156.762 | Windward | 1917–32, 1937–P | 93 | Natural | C W |
| C8 | A | USGS | 16417800 | LB Honoulimaloo Str US diversion, Molokai, HI | 730 | 21.128 | −156.753 | Windward | P (LF only) | 0 | Natural | C W |
| C9 | A | USGS | 16417200 | Kainalu Stream nr Pauwalu, Molokai, HI | 290 | 21.095 | −156.779 | Leeward | P (LF only) | 0 | Natural | C W |
| C10 | N | na | 16416000 | Punaula Gulch nr Pukoo, Molokai, HI | 1,200 | 21.094 | −156.811 | Leeward | 1947–72 | 24 | Natural | C W |
| C11 | A | USGS | 16415000 | EF Kawela Gulch nr Kamalo, Molokai, HI | 3,620 | 21.110 | −156.903 | Leeward | 1946–71, P (LF only) | 24 | Natural | C W |
| C12 | A | USGS | 16415600 | Kawela Gulch near Moku, Molokai, HI | 40 | 21.070 | −156.948 | Leeward | 2004–11, 2016–P | 9 | Regulated | W |
| Partial-record stations | | | | | | | | | | | | |
| P1 | A | USGS | 210815156451801 | Papio Gulch nr alt. 1100 ft, Molokai, HI | 1,100 | 21.138 | −156.755 | Windward | P | 1 | Natural | W |
| P2 | A | USGS | 210723156461301 | Honouliwai Str nr alt. 1200 ft, Molokai, HI | 1,200 | 21.123 | −156.770 | Windward | P | 1 | Natural | W |
| P3 | A | USGS | 210631156460301 | Waialua Stream nr alt. 300 ft, Molokai, HI | 300 | 21.109 | −156.768 | Windward | P | 1 | Natural | W |

**Table 13.** Continuous-record streamflow-gaging stations and partial-record stations in the surface-water monitoring program for Molokaʻi, Hawaiʻi.—Continued

| Map ID[1] | Status[2] | Operating agency | Station number[3] | Station name[4] or description[5] | Altitude,[6] in feet | Latitude[7] | Longitude[7] | Aspect | Period of record | Years of record[8] | Flow classification | Network[9] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Partial-record stations—Continued | | | | | | | | | | | | |
| P4 | A | USGS | 210530156471201 | Honomuni Gl nr alt. 250 ft, Molokai, HI | 250 | 21.092 | −156.787 | Leeward | P | 1 | Natural | W |
| P5 | A | USGS | 210645156542501 | W Fork Kawela US diversion nr 3685 ft, Molokai, HI | 3,680 | 21.112 | −156.907 | Leeward | 2010, P | 2 | Natural | W |
| P6 | A | USGS | 210706156544801 | LB SF Kaunakakai Gl nr alt. 3650 ft, Molokai, HI | 3,650 | 21.118 | −156.913 | Leeward | P | 1 | Natural | W |
| P7 | A | USGS | 210725156550501 | RB SF Kaunakakai Gl nr alt. 3500 ft, Molokai, HI | 3,500 | 21.124 | −156.918 | Leeward | P | 1 | Natural | W |
| P8 | A | USGS | 210833156582501 | Kuhuaawi Gulch at alt 1900 ft, Molokai HI | 1,900 | 21.143 | −156.974 | Leeward | P | 1 | Natural | W |

[1]Map identification number illustrated in figure 13.

[2]Status of "A" represents an active station as of 2018. Status of "N" represents an additional station needed to supplement the current (2018) program.

[3]Station with a status of "N" that is not a reactivation of an inactive USGS station does not have a station number.

[4]NWIS and CWRM database limitations preclude the use of Hawaiian diacritical marks in station names.

[5]Station with a status of "N" that is not a reactivation of an inactive USGS station does not have a station name; instead, a station description is provided.

[6]Altitude values interpolated from USGS 1:24,000-scale digital hypsography data and rounded to the nearest ten.

[7]Latitude and longitude coordinates in North American Datum of 1983.

[8]For USGS stations, number of years of complete continuous record as of the end of 2018 water year. A water year is a 12-month period that extends from October 1 to September 30 of the following year and is named according to the year during which the period ends. For CWRM stations, an estimate of the number of years of continuous record as of the end of 2018 water year is included.

[9]A station can be in one or both of the following networks: "C" represents Climate-Response Network. "W" represents Water-Management Network.

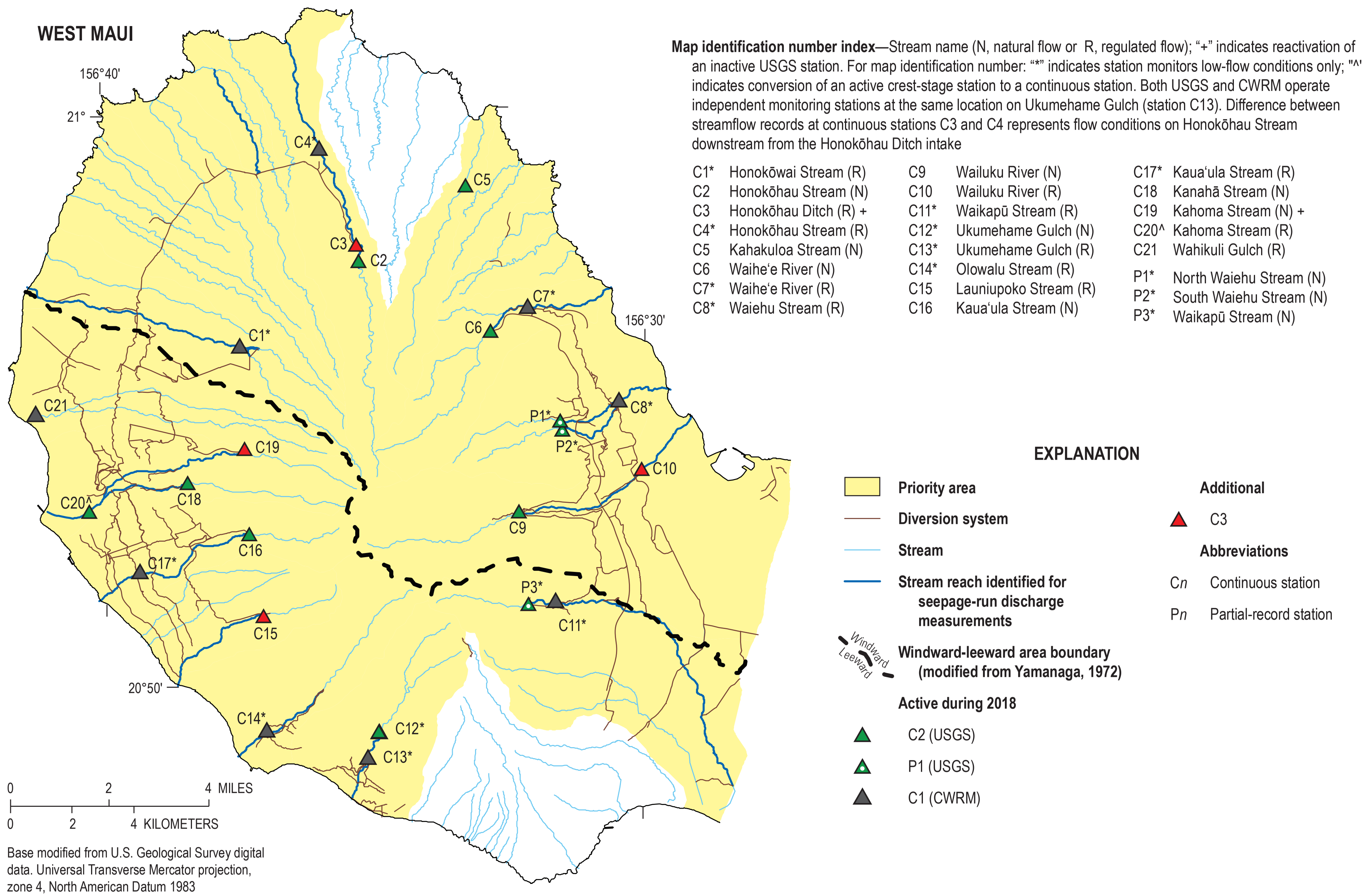
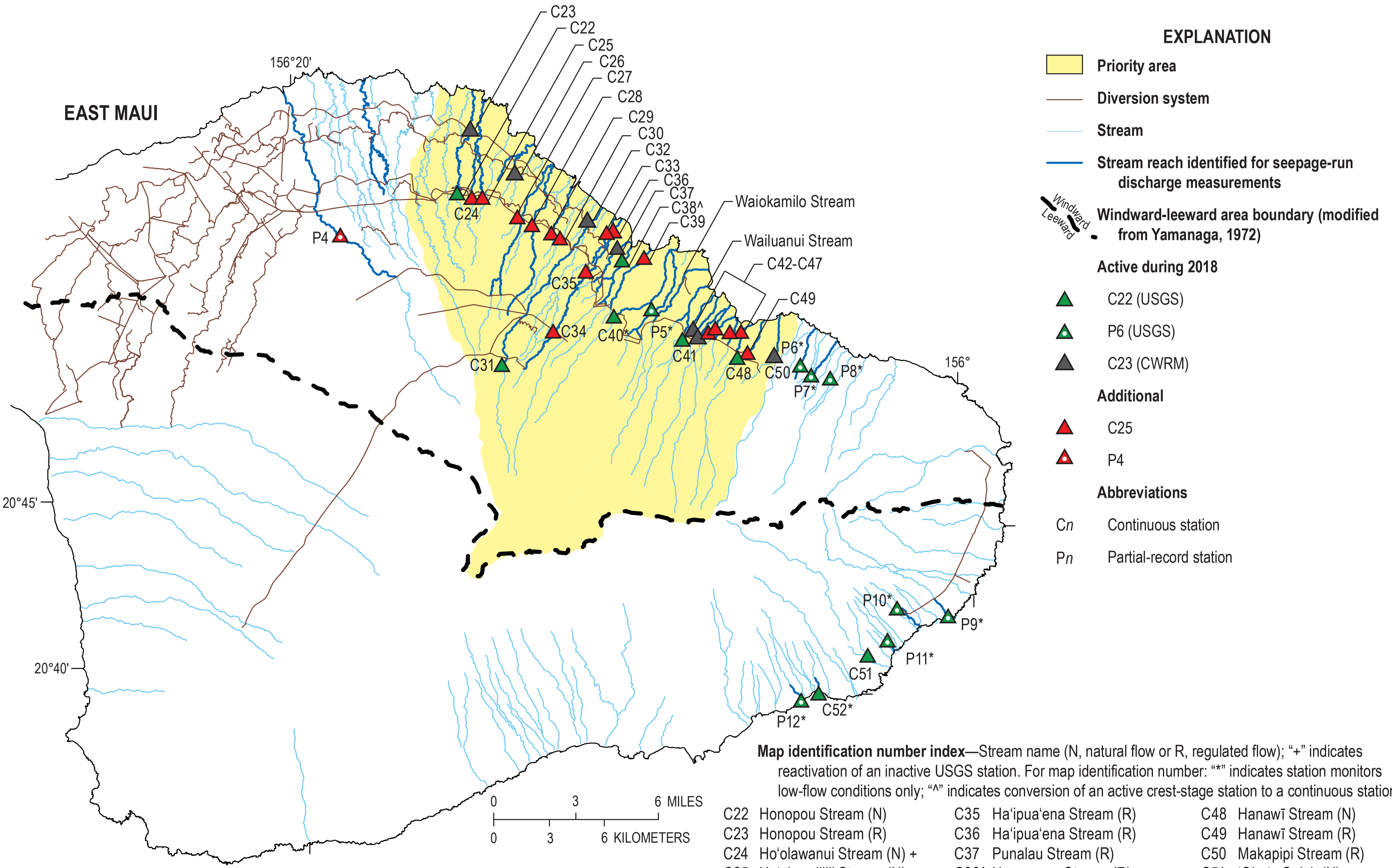



**Figure 14.** Map showing the surface-water monitoring program on west Maui, Hawai‘i. Surface-water monitoring stations are listed with their map identification number. Operating agencies include the U.S. Geological Survey (USGS) and the State of Hawai‘i Commission on Water Resource Management (CWRM).




**Map identification number index**—Stream name (N, natural flow or R, regulated flow); "+" indicates reactivation of an inactive USGS station. For map identification number: "*" indicates station monitors low-flow conditions only; "^" indicates conversion of an active crest-stage station to a continuous station

C22 Honopou Stream (N)
C23 Honopou Stream (R)
C24 Ho'olawanui Stream (N) +
C25 Ho'olawaliilii Stream (N) +
C26 Hanehoi Stream (R)
C27 Kailua Stream (R) +
C28 Nailiihaele Stream (N) +
C29 'O'opuola Stream (N) +
C30 Ka'aiea Gulch (N) +
C31 Waikamoi Stream (N)
C32 Waikamoi Stream (R)
C33 Puohokamoa Stream (R)
C34 Ha'ipua'ena Stream (N) +
C35 Ha'ipua'ena Stream (R)
C36 Ha'ipua'ena Stream (R)
C37 Punalau Stream (R)
C38^ Honomanū Stream (R)
C39 Nua'ailua Stream (R)
C40* Pi'ina'au Stream (N)
C41 West Wailua Iki Stream (N)
C42 East Wailua Iki Stream (R)
C43 Kopiliula Stream (R)
C44 Pua'aka'a Stream (N)
C45 Pa'akea Gulch (R)
C46 Waiaaka Stream (R)
C47 Kapaula Gulch (R)
C48 Hanawī Stream (N)
C49 Hanawī Stream (R)
C50 Makapipi Stream (R)
C51 'Ohe'o Gulch (N)
C52* Kukui'ula Gulch (N)
P4 Māliko Gulch (N)
P5* Palauhulu Stream (N)
P6* Kālepalehua Gulch (N)
P7* Kahawaihapapa Gulch (N)
P8* Lanikele Gulch (N)
P9* Papahawahawa Gulch (N)
P10* Wailua Stream (N)
P11* Hāhālawe Gulch (N)
P12* Alelele Stream (N)

Base modified from U.S. Geological Survey digital data. Universal Transverse Mercator projection, zone 4, North American Datum 1983

**Figure 15.** Map showing the surface-water monitoring program on east Maui, Hawai'i. Surface-water monitoring stations are listed with their map identification number. Operating agencies include the U.S. Geological Survey (USGS) and the State of Hawai'i Commission on Water Resource Management (CWRM).

**Table 14.** Continuous-record streamflow-gaging stations and partial-record stations in the surface-water monitoring program for Maui, Hawaiʻi.

[ab, above; abv, above; bdy, boundary; conf, confluence; CWRM, State of Hawaiʻi Commission on Water Resource Management; DS, downstream; Dt, Ditch; Dtch, Ditch; ft, feet; Gl, gulch; HI, Hawaii; Hwy, highway; intk, intake; LF, low flow; na, not applicable; nr, near; P, present (2018); PL, pipeline; Rv, River; Riv, River; S, south, Str, Stream; US, upstream; USGS, U.S. Geological Survey]

| Map ID[1] | Status[2] | Operating agency | Station number[3] | Station name[4] or description[5] | Altitude[6], in feet | Latitude[7] | Longitude[7] | Aspect | Period of record | Years of record[8] | Flow classification | Network[10] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Continuous stations | | | | | | | | | | | | |
| C1 | A | CWRM | 6-124 | Honokowai Stream below confluence | 1,400 | 20.932 | −156.625 | Windward | 2017–P | 1 | Regulated | W |
| C2 | A | USGS | 16620000 | Honokohau Stream near Honokohau, Maui, HI | 870 | 20.962 | −156.588 | Windward | 1913–20, 1922–88, 1990–P | 99 | Natural | C W |
| C3 | N | na | 16621000 | Honokohau Ditch at intake nr Honokohau, Maui, HI | 840 | 20.961 | −156.587 | Windward | 1907–1913 | 5 | Regulated | W |
| C4 | A | CWRM | 6-149 | Honokohau Stream at McDonald's Dam | 250 | 20.995 | −156.601 | Windward | P | 0 | Regulated | W |
| C5 | A | USGS | 16618000 | Kahakuloa Stream near Honokohau, Maui, HI | 330 | 20.979 | −156.554 | Windward | 1939–43, 1947–70, 1974–P | 68 | Natural | C |
| C6 | A | USGS | 16614000 | Waihee Rv abv Waihee Dtch intk nr Waihee, Maui, HI | 600 | 20.936 | −156.547 | Windward | 1983–P | 33 | Natural | C W |
| C7 | A | CWRM | 6-68 | Waihee River below Spreckles Ditch | 340 | 20.943 | −156.535 | Windward | 2010–P | 8 | Regulated | W |
| C8 | A | CWRM | 6-69 | Waiehu Stream below confluence | 200 | 20.914 | −156.507 | Windward | 2010–P | 8 | Regulated | W |
| C9 | A | USGS | 16604500 | Wailuku River at Kepaniwai Park, Maui, HI | 780 | 20.882 | −156.539 | Windward | 1983–P | 34 | Natural | C W |
| C10 | N | USGS | na | Wailuku River at Wailuku, Maui, HI | 160 | 20.896 | −156.499 | Windward | na | na | Regulated | W |
| C11 | A | CWRM | 6-88 | Waikapu Stream at 915 ft | 920 | 20.856 | −156.528 | Leeward | 2017–P | 1 | Regulated | W |
| C12 | A | USGS | 16647000 | Ukumehame Gulch nr Olowalu, Maui, HI | 400 | 20.819 | −156.584 | Leeward | 1911, 1913–19, P (LF only) | 3 | Natural | C W |
| C12 | A | CWRM | 6-118 | Ukumehame Gulch at 410 ft | 410 | 20.819 | −156.584 | Leeward | 2017–P | 1 | Natural | C W |
| C13 | A | CWRM | 6-119 | Ukumehame Gulch at 180 ft | 180 | 20.811 | −156.587 | Leeward | 2017–P | 1 | Regulated | W |
| C14 | A | CWRM | 6-121 | Olowalu Stream below lower diversion | 140 | 20.820 | −156.618 | Leeward | 2017–P | 1 | Regulated | W |
| C15 | N | na | na | Launiopoko Stream downstream West Maui Land diversion intake | 1,160 | 20.854 | −156.619 | Leeward | na | na | Regulated | W |

**Table 14.** Continuous-record streamflow-gaging stations and partial-record stations in the surface-water monitoring program for Maui, Hawai‘i.—Continued

| Map ID[1] | Status[2] | Operating agency | Station number[3] | Station name[4] or description[5] | Altitude[6], in feet | Latitude[7] | Longitude[7] | Aspect | Period of record | Years of record[8] | Flow classification | Network[10] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Continuous stations—Continued | | | | | | | | | | | | |
| C16 | A | USGS | na | Kauaula Stream upstream and downstream of intake | na | na | na | Leeward | To be installed | na | Natural | C W |
| C17 | A | CWRM | 6-122 | Kauaula Stream below siphon | 260 | 20.866 | −156.657 | Leeward | 2017–P | 1 | Regulated | W |
| C18 | A | USGS | 16636000 | Kanaha Stream ab PL Intake nr Lahaina, Maui, HI | 1,060 | 20.893 | −156.642 | Leeward | 1916–32 | 13 | Natural | C W |
| C19 | N | na | 16634000 | Kahoma Stream nr Lahaina, Maui, HI | 1,940 | 20.901 | −156.623 | Leeward | 1911, 1913–17 | 3 | Natural | C W |
| C20 | A | USGS | 16638500 | Kahoma Stream at Lahaina, Maui, HI | 100 | 20.885 | −156.673 | Leeward | 1962–89, 1989–P (peak flow only) | 26 | Regulated | W |
| C21 | A | CWRM | 6-155 | Wahikuli Gulch at mouth | 5 | 20.913 | −156.689 | Leeward | P | 0 | Regulated | W |
| C22 | A | USGS | 16587000 | Honopou Stream near Huelo, Maui, HI | 1,210 | 20.886 | −156.252 | Windward | 1911–P | 107 | Natural | C W |
| C23 | A | CWRM | 6-59 | Honopou Stream near bridge downstream of Haiku Ditch | 390 | 20.916 | −156.245 | Windward | 2009–P | 9 | Regulated | W |
| C24 | N | na | 16585000 | Hoolawanui Stream nr Huelo, Maui, HI | 1,220 | 20.884 | −156.245 | Windward | 1911–71 | 60 | Natural | W |
| C25 | N | na | 16586000 | Hoolawaliilii Stream near Huelo, Maui, HI | 1,240 | 20.885 | −156.240 | Windward | 1912–57 | 45 | Natural | W |
| C26 | A | CWRM | 6-60 | Hanehoi Stream above Lowrie Ditch | 660 | 20.895 | −156.224 | Windward | 2009–P | 9 | Regulated | W |
| C27 | N | na | 16577000 | Kailua Stream near Huelo, Maui, HI | 1,250 | 20.873 | −156.221 | Windward | 1913–58 | 40 | Regulated | W |
| C28 | N | na | 16570000 | Nailiilihaele Stream near Huelo, Maui, HI | 1,220 | 20.871 | −156.216 | Windward | 1911, 1913–75 | 55 | Natural | C W |
| C29 | N | na | 16566000 | Oopuola Stream near Huelo, Maui, HI | 1,200 | 20.868 | −156.205 | Windward | 1930–57 | 27 | Natural | W |
| C30 | N | na | 16565000 | Kaaiea Gulch near Huelo, Maui, HI | 1,310 | 20.864 | −156.202 | Windward | 1922–62 | 39 | Natural | W |
| C31 | A | USGS | 16552800 | Waikamoi Str abv Kula PL intake nr Olinda, Maui, HI | 4,490 | 20.805 | −156.231 | Windward | 1953–68, 2009–P | 22 | Natural | C W |
| C32 | A | CWRM | 6-67 | Waikamoi Stream near Hana Highway | 560 | 20.872 | −156.187 | Windward | 2010–P | 8 | Regulated | W |

**Table 14.** Continuous-record streamflow-gaging stations and partial-record stations in the surface-water monitoring program for Maui, Hawaiʻi.—Continued

| Map ID[1] | Status[2] | Operating agency | Station number[3] | Station name[4] or description[5] | Altitude[6], in feet | Latitude[7] | Longitude[7] | Aspect | Period of record | Years of record[8] | Flow classification | Network[10] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Continuous stations—Continued | | | | | | | | | | | | |
| C33 | N | na | 6-224 | Puohokamoa Stream at Hana Highway | 570 | 20.867 | −156.179 | Windward | na | na | Regulated | W |
| C34 | N | na | 16531100 | Haipuaena Str at Kula PL intk nr Olinda, Maui, HI | 4,320 | 20.803 | −156.221 | Windward | 1946–68 | 21 | Natural | C W |
| C35 | N | na | 16536000 | Haipuaena Str ab Spreckels Ditch nr Huelo, Maui | 1,510 | 20.848 | −156.189 | Windward | 1913–67 | 52 | Regulated | W |
| C36 | N | na | na | Haipuaena Stream at Hana Highway | 490 | 20.866 | −156.176 | Windward | na | na | Regulated | W |
| C37 | A | CWRM | 6-170 | Punalau Stream at Hana Highway | 80 | 20.861 | −156.170 | Windward | P | 0 | Regulated | W |
| C38 | A | USGS | 16527500 | Honomanu Stream near Hana Hwy, Maui, HI | 60 | 20.853 | −156.170 | Windward | 2015–P (peak flow only) | na | Regulated | W |
| C39 | N | na | 6-202 | Nuaailua Stream at Hana Highway | 110 | 20.855 | −156.161 | Windward | na | na | Regulated | W |
| C40 | A | USGS | 16522950 | Piinaau Str 470 ft US Koolau Ditch, Maui, HI | 1,350 | 20.827 | −156.175 | Windward | P (LF only) | na | Natural | C W |
| C41 | A | USGS | 16518000 | West Wailuaiki Stream near Keanae, Maui, HI | 1,550 | 20.814 | −156.143 | Windward | 1914–17, 1921–P | 97 | Natural | C W |
| C42 | A | CWRM | 6-66 | East Wailuaiki Stream near Hana Highway | 1,240 | 20.820 | −156.136 | Windward | 2010–P | 7 | Regulated | W |
| C43 | A | CWRM | 6-102 | Kopiliula Stream below Hana Highway | 1,250 | 20.817 | −156.134 | Windward | 2017–P | 1 | Regulated | W |
| C44 | N | na | na | Puaakaa Stream at Hana Highway | 1,240 | 20.817 | −156.128 | Windward | na | na | Natural | W |
| C45 | N | na | na | Paakea Stream at Hana Highway | 1,260 | 20.814 | −156.119 | Windward | na | na | Regulated | W |
| C46 | N | na | na | Waiaaka Stream downstream Hana Highway | 1,170 | 20.814 | −156.117 | Windward | na | na | Regulated | W |
| C47 | N | na | na | Kapalua Stream at Hana Highway | 1,190 | 20.811 | −156.115 | Windward | na | na | Regulated | W |
| C48 | A | USGS | 16508000 | Hanawi Stream near Nahiku, Maui, HI | 1,320 | 20.807 | −156.114 | Windward | 1914–15, 1921–P | 96 | Natural | C W |
| C49 | N | na | na | Hanawi Stream at Hana Highway | 1,050 | 20.809 | −156.109 | Windward | na | na | Regulated | W |

**Table 14.** Continuous-record streamflow-gaging stations and partial-record stations in the surface-water monitoring program for Maui, Hawai'i.—Continued

| Map ID[1] | Status[2] | Operating agency | Station number[3] | Station name[4] or description[5] | Altitude[6], in feet | Latitude[7] | Longitude[7] | Aspect | Period of record | Years of record[8] | Flow classification | Network[10] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Continuous stations—Continued | | | | | | | | | | | | |
| C50 | A | CWRM | 6-72 | Makapipi Stream near Hana Highway | 920 | 20.807 | −156.096 | Windward | 2010–P | 8 | Regulated | W |
| C51 | A | USGS | 16501200 | Oheo Gulch at dam near Kipahulu, Maui, HI | 420 | 20.668 | −156.052 | Leeward | 1988–97, 2002–11, 2014–P | 22 | Natural | C W |
| C52 | A | USGS | 16500800 | Kukuiula Gulch near Kipahulu, Maui, HI | 120 | 20.652 | −156.076 | Leeward | 1963–68, P (LF only) | 2 | Natural | C W |
| Partial-record stations | | | | | | | | | | | | |
| P1 | A | USGS | 205458156315401 | North Waiehu Stream above intake, Maui, HI | 660 | 20.910 | −156.526 | Windward | P | 5[9] | Natural | W |
| P2 | A | USGS | 205427156312901 | South Waiehu Stream above intake, Maui, HI | 620 | 20.907 | −156.525 | Windward | P | 4[9] | Natural | W |
| P3 | A | USGS | 205121156321101 | Waikapu Str 120ft US S Waikapu Dt intake, Maui, HI | 1,160 | 20.856 | −156.536 | Leeward | P | 4[9] | Natural | W |
| P4 | N | na | na | Maliko Gulch 1.4 miles upstream Wailoa Ditch | 1,320 | 20.868 | −156.311 | Windward | na | na | Natural | W |
| P5 | A | USGS | 204946156092101 | Palauhulu Str 0.9 mi DS Kano Str conf, Maui, HI | 760 | 20.830 | −156.156 | Windward | Station established in 2018 | 1[9] | Natural | W |
| P6 | A | USGS | 204820156050001 | Kalepalehua Gulch at Hana Hwy, Maui, HI | 870 | 20.806 | −156.083 | Windward | Station established in 2018 | 0[9] | Natural | W |
| P7 | A | USGS | 204804156043901 | Kahawaihapapa Gulch at Hana Hwy, Maui, HI | 860 | 20.801 | −156.077 | Windward | Station established in 2018 | 0[9] | Natural | W |
| P8 | A | USGS | 204756156040401 | Lanikele Gulch at Hana Hwy, Maui, HI | 740 | 20.799 | −156.068 | Windward | Station established in 2018 | 0[9] | Natural | W |
| P9 | A | USGS | 204113156004001 | Papahawahawa Gulch at Hana Hwy, Maui, HI | 130 | 20.687 | −156.011 | Leeward | P | 0[9] | Natural | W |
| P10 | A | USGS | 204129156025901 | Wailua Str 0.33mi DS Waihiumalu Falls, Maui, HI | 1,040 | 20.691 | −156.050 | Leeward | P | 0[9] | Natural | W |
| P11 | A | USGS | 204026156022601 | Hahalawe Gl at Hana Hwy, Maui, HI | 340 | 20.674 | −156.040 | Leeward | 1969, 1984 | 3[9] | Natural | W |

**Table 14.** Continuous-record streamflow-gaging stations and partial-record stations in the surface-water monitoring program for Maui, Hawai‘i.—Continued

| Map ID[1] | Status[2] | Operating agency | Station number[3] | Station name[4] or description[5] | Altitude[6], in feet | Latitude[7] | Longitude[7] | Aspect | Period of record | Years of record[8] | Flow classification | Network[10] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Partial-record stations—Continued | | | | | | | | | | | | |
| P12 | A | USGS | 203901156050901 | Alelele Stream above Hana Hwy, Maui, HI | 100 | 20.650 | −156.086 | Leeward | P | 3[9] | Natural | W |

[1]Map identification number illustrated in figures 14 and 15.

[2]Status of “A” represents an active station as of 2018. Status of “N” represents an additional station needed to supplement the current (2018) program.

[3]Station with a status of “N” that is not a reactivation of an inactive USGS station does not have a station number.

[4]NWIS and CWRM database limitations preclude the use of Hawaiian diacritical marks in station names.

[5]Station with a status of “N” that is not a reactivation of an inactive USGS station does not have a station name; instead, a station description is provided.

[6]Altitude values interpolated from USGS 1:24,000-scale digital hypsography data and rounded to the nearest ten.

[7]Latitude and longitude coordinates in North American Datum of 1983.

[8]For USGS stations, number of years of complete continuous record as of the end of 2018 water year. A water year is a 12-month period that extends from October 1 to September 30 of the following year and is named according to the year during which the period ends. For CWRM stations, an estimate of the number of years of continuous record as of the end of 2018 water year is included.

[9]Number of measurements within the indicated period of record as of May 2019.

[10]A station can be in one or both of the following networks: “C” represents Climate-Response Network. “W” represents Water-Management Network.

monitor a majority of the remaining streams with active diversions. Although all EMI diversions on Honopou and Hanehoi Streams have been abandoned, continuous stations C23, C24, and C28 are included to monitor water availability for supporting traditional and cultural practices and native stream life. An active crest-stage station on Honomanū Stream (C38) can be converted to a continuous streamflow-gaging station to monitor diverted-flow conditions. Long-term active stations that monitor natural flow on Honopou (C22), West Wailua Iki (C41), and Hanawī (C49) Streams are important index stations for the partial-record stations in east Maui. Pi‘ina‘au Stream is located in an under-represented hydrogeologic setting on the island—the thickly saturated setting in the Ke‘anae aquifer system (see “Setting” for the “Groundwater” section; table 14); therefore, monitoring station C40 is included in the monitoring program.

Ten monitoring stations are selected for non-priority areas in east Maui because existing hydrologic data are limited for these areas, and additional data are needed for developing instream-flow standards. The continuous station on Kukui‘ula Gulch (C52) and all partial-record stations (P5–P12) except that on Māliko Gulch (P4) were established as part of the 2018 statewide low-flow study to describe natural flow characteristics in the area. The long-term continuous station on ‘Ohe‘o Gulch (C51) and low-flow continuous station on Kukui‘ula Gulch (C52) are potential index stations.

### Hawai‘i

The resource-management network for Hawai‘i island is represented by 11 continuous stations and 19 partial-record stations (fig. 16, table 15). Surface-water priority areas consist of drainage basins in the northwestern, eastern, and southern parts of the island. Monitoring stations selected in priority areas are mainly for the development of instream-flow standards for streams that support agriculture and hydropower production. East Branch Honokāne Nui Stream (C2; fig. 16, table 15) supports diversified agriculture in Kohala. The tributaries of Wailoa Stream (C5)—Kawainui and Alakahi Streams (C3, C4)—are diverted by two separate ditches to support diversified agriculture in the Kohala area, and commercial forestry and cattle operations in the Hāmākua area (fig. 1; Hawai‘i County, 2010, p. 801-15–801-16; State of Hawai‘i, 2016b, p. 75–76). Station C5 is intended to characterize effects of the diversions in the tributaries of Waipio Stream on water availability for downstream uses. Hydropower provided about 2.8 percent of Hawai‘i island’s energy needs in 2017 (State of Hawai‘i, 2018a, p. 27), and a majority of the hydropower facilities on Hawai‘i island are located on the eastern side of the island. Wailuku River (C9, C10) and its tributaries support multiple hydropower facilities, including the largest operating hydropower facility in the State. Station C9 records the natural flow characteristics of the river, and station C10—downstream from the upper diversions but upstream from the hydropower facility’s return flow—characterizes effects of the main diversions on streamflow. Waikoloa (C15), Kohākōhau (P17), Keawewai (P18), and Waipāhoehoe (P19) Streams support cattle operations and agriculture in Kohala (Hawai‘i County, 2010, p. 801–14, 801–20).

Surface-water priority areas in the northwestern part of the island have limited hydrologic data, and streams in the areas were historically diverted by an irrigation ditch, which is currently used for recreational purposes. A monitoring need is identified for Waiakauaua Gulch (P1), East Branch Hālawa Gulch (P2), Niuli‘i Stream (P3), ‘Āwini Puali Gulch (C1), East Branch Honokāne Nui Stream (C2), Kukui Stream (P4), and Kaimū Stream (P5) to fill an important data gap in developing instream-flow standards. Continuous stations C1 and C2 are potential index stations, and C1, P1, and P3 were established as part of the 2018 statewide low-flow study.

Many monitoring stations are selected in non-priority areas because existing hydrologic data are limited, and additional data are needed for developing instream-flow standards. Monitoring stations (C6, C7, P6–P16) just north of Hilo, Hawai‘i (fig. 1) were established as part of the 2018 statewide low-flow study, and the continuous station on Honoli‘i Stream (C8) is a needed index station.

## Climate-Response Network

Active continuous stations with long-term records of natural streamflow generally were included in the climate-response network of the monitoring program because of their importance in determining streamflow characteristics and analyzing long-term streamflow trends using the long-term monitoring data-collection strategy. Records at these continuous stations provided satisfactory statistical correlations with discrete data at partial-record stations in previous low-flow investigations. Generally, the different hydrologic settings on Kaua‘i, O‘ahu, and Maui are represented by the active continuous stations selected for the monitoring program. Additional monitoring is needed for some areas on Moloka‘i and Hawai‘i island.

On Kaua‘i, the climate-response network is represented by 10 continuous stations, which consist of 8 active stations and 2 USGS inactive continuous stations selected for reactivation (fig. 11, table 11). Seven of the active continuous stations have a period of record longer than 50 years, and 2 of these stations, east branch of North Fork Wailuā River (C9) and Kawaikōī Stream (C20), have over 100 years of record. Inactive USGS continuous stations on Kalalau (C1) and Lāwa‘i (C15) streams are selected for reactivation because hydrologic information in those areas are scarce.

O‘ahu’s climate-response network is represented by 18 continuous stations (fig. 12, table 12). Eleven of the 16 active continuous stations have over 50 years of record, and 2 of these stations, Waiakeakua Stream (C19) and Kalihi Stream (C23), have 100 years of record or more. The leeward area constitutes a larger part of the island that consists of 12 continuous stations. In the northern part of the island, where hydrologic data are limited, the inactive USGS continuous station on Mālaekahana Stream (C1) is selected for reactivation, and the active USGS crest-stage station on Kamananui Stream (C40) can be converted to a continuous streamflow-gaging station. A large part of central O‘ahu lies within an under-represented hydrogeologic setting (see “Setting” for the “Groundwater” section) where four stations (C31–C33, C39) are selected for characterizing climate-change effects on streamflow.

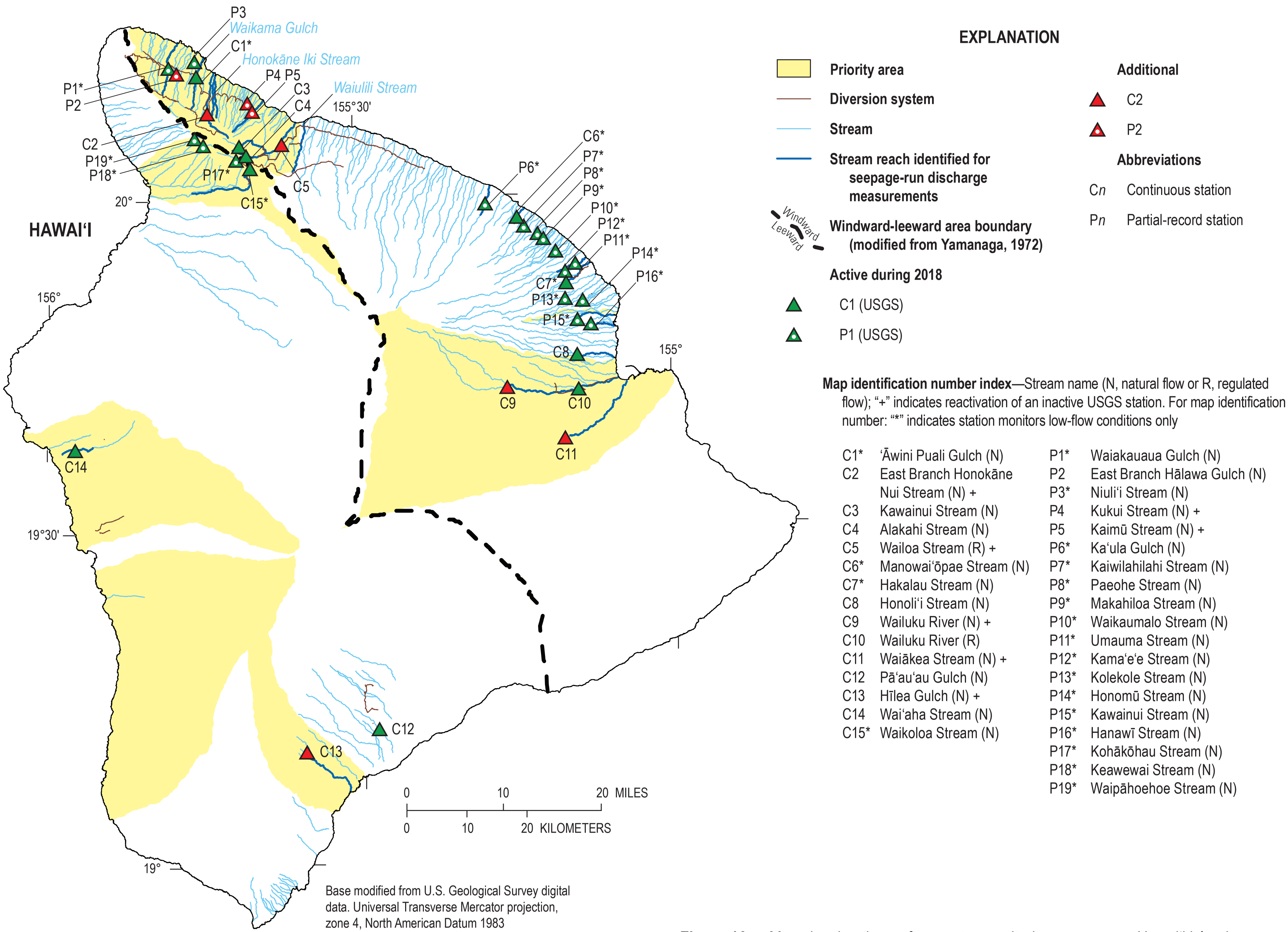



**Figure 16.** Map showing the surface-water monitoring program on Hawai‘i island, Hawai‘i. Surface-water monitoring stations are listed with their map identification number. Operating agency includes the U.S. Geological Survey (USGS).

**Table 15.** Continuous-record streamflow-gaging stations and partial-record stations in the surface-water monitoring program for Hawai‘i island, Hawai‘i.

[alt, altitude; Br, Branch; CWRM, State of Hawai‘i Commission on Water Resource Management; E, East; ft, feet; Gl, Gulch; HI, Hawaii; Hwy, Highway; LF, low flow; mi, mile; na, not applicable; nr, near; P, present (2018); US, upstream; USGS, U.S. Geological Survey]

| Map ID[1] | Status[2] | Operating agency | Station number[3] | Station name[4] or description[5] | Altitude,[6] in feet | Latitude[7] | Longitude[7] | Aspect | Period of record | Years of record[8] | Flow classification | Network[10] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Continuous stations | | | | | | | | | | | | |
| C1 | A | USGS | 16751500 | Awini Puali Gulch US of Kohala Ditch, HI | 1,000 | 20.192 | −155.748 | Windward | P (LF only) | 0 | Natural | C W |
| C2 | N | na | 16747500 | E Br Honokane Nui Stream near Nuilii, HI | 1,080 | 20.135 | −155.731 | Windward | 1963–65 | 2 | Natural | C W |
| C3 | A | USGS | 16720000 | Kawainui Stream nr Kamuela, HI | 4,060 | 20.085 | −155.681 | Windward | 1964–P | 53 | Natural | C W |
| C4 | A | USGS | 16725000 | Alakahi Stream near Kamuela, HI | 3,900 | 20.071 | −155.671 | Windward | 1964–P | 54 | Natural after 1997 | C W |
| C5 | N | na | 16732200 | Wailoa Stream near Waipio, HI | 150 | 20.088 | −155.614 | Windward | 1964–69 | 4 | Regulated | W |
| C6 | A | USGS | 16717815 | Manowaiopae Stream near Spencer Road, HI | 970 | 19.972 | −155.243 | Windward | P (LF only) | 0 | Natural | C W |
| C7 | A | USGS | 16717700 | Hakalau Stream nr alt 1300 ft, HI | 1,300 | 19.872 | −155.167 | Windward | P (LF only) | 0 | Natural | C W |
| C8 | A | USGS | 16717000 | Honolii Stream nr Papaikou, HI | 1,540 | 19.764 | −155.152 | Windward | 1911–13, 1967–P | 52 | Natural | C W |
| C9 | N | na | 16701800 | Wailuku River nr Kaumana, HI | 3,520 | 19.718 | −155.266 | Windward | 1966–82 | 15 | Natural | C W |
| C10 | A | USGS | 16704000 | Wailuku River at Piihonua, HI | 1,090 | 19.712 | −155.151 | Windward | 1928–P | 87 | Regulated prior to 1968 and after 5/1993 | W |
| C11 | N | na | 16700000 | Waiakea Stream nr Mountain View, HI | 1,930 | 19.639 | −155.172 | Windward | 1930–95 | 65 | Natural | C |
| C12 | A | USGS | 16770500 | Paauau Gulch at Pahala, HI | 970 | 19.208 | −155.477 | Leeward | 1962–79, 2001–P | 33 | Natural | C |
| C13 | N | na | 16764000 | Hilea Gulch Tributary near Honuapo, HI | 2,940 | 19.171 | −155.597 | Leeward | 1966–91 | 25 | Natural | C |
| C14 | A | USGS | 16759600 | Waiaha Stream at Holualoa, HI | 1,490 | 19.634 | −155.950 | Leeward | 2002–03, 2016–P | 2 | Natural | C |
| C15 | A | USGS | 16757000 | Waikoloa Stream nr Kamuela, HI | 3,570 | 20.052 | −155.664 | Leeward | 1947–71, P (LF only) | 23 | Natural | C W |

**Table 15.** Continuous-record streamflow-gaging stations and partial-record stations in the surface-water monitoring program for Hawai‘i island, Hawai‘i.—Continued

| Map ID[1] | Status[2] | Operating agency | Station number[3] | Station name[4] or description[5] | Altitude,[6] in feet | Latitude[7] | Longitude[7] | Aspect | Period of record | Years of record[8] | Flow classification | Network[10] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Partial-record stations | | | | | | | | | | | | |
| P1 | A | USGS | 201222155472801 | Waiakauaua Gl 100 ft US of access road, HI | 1,010 | 20.206 | −155.791 | Windward | P | 1[9] | Natural | W |
| P2 | N | na | na | East Branch Hālawa Gulch US bridge, HI | 1,300 | 20.196 | −155.778 | Windward | na | na | Natural | W |
| P3 | A | USGS | 201251155444801 | Niulii Stream US of access road bridge, HI | 350 | 20.214 | −155.747 | Windward | P | 1[9] | Natural | W |
| P4 | N | na | 16742000 | Kukui Stream near Waimanu, HI | 1,940 | 20.151 | −155.668 | Windward | 1939–52, 1959–66 | 19 | Natural | W |
| P5 | N | na | 16738000 | Kaimu Stream near Waimanu, HI | 1,980 | 20.139 | −155.661 | Windward | 1939–47, 1950–52 | 8 | Natural | W |
| P6 | A | USGS | 195939155173301 | Kaula Gulch nr alt 1,400 ft, HI | 1,400 | 19.994 | −155.293 | Windward | Station established in 2018 | 1[9] | Natural | W |
| P7 | A | USGS | 195732155135601 | Kaiwilahilahi Stream at alt 1,100 ft, HI | 1,100 | 19.959 | −155.232 | Windward | P | 3[9] | Natural | W |
| P8 | A | USGS | 195647155123901 | Paeohe Stream nr Maulua Bay, HI | 1,070 | 19.946 | −155.212 | Windward | Station established in 2018 | 3[9] | Natural | W |
| P9 | A | USGS | 195622155120801 | Makahiloa Stream at alt 920 ft, HI | 920 | 19.940 | −155.202 | Windward | Station established in 2018 | 2[9] | Natural | W |
| P10 | A | USGS | 195512155105801 | Waikaumalo Stream at road crossing, HI | 1,140 | 19.920 | −155.183 | Windward | Station established in 2018 | 3[9] | Natural | W |
| P11 | A | USGS | 195400155091501 | Umauma Stream nr alt 630 ft, HI | 630 | 19.900 | −155.154 | Windward | Station established in 2018 | 2[9] | Natural | W |
| P12 | A | USGS | 195321155100301 | Kamaee Stream 2.7 mi west of Hakalau, HI | 1,120 | 19.889 | −155.168 | Windward | Station established in 2018 | 5[9] | Natural | W |
| P13 | A | USGS | 195056155100801 | Kolekole Stream nr alt 1,650 ft, HI | 1,650 | 19.848 | −155.170 | Windward | P | 3[9] | Natural | W |
| P14 | A | USGS | 195044155082801 | Honomu Stream at alt 1,050 ft, HI | 1,050 | 19.846 | −155.141 | Windward | P | 3[9] | Natural | W |
| P15 | A | USGS | 194901155090101 | Kawainui Stream nr alt 1,600 ft, HI | 1,600 | 19.817 | −155.150 | Windward | Station established in 2018 | 2[9] | Natural | W |
| P16 | A | USGS | 194831155073601 | Hanawi Stream nr alt 900 ft, HI | 900 | 19.809 | −155.127 | Windward | Station established in 2018 | 2[9] | Natural | W |
| P17 | A | USGS | 16756000 | Kohakohau Stream near Kamuela, HI | 3,510 | 20.048 | −155.680 | Leeward | 1956–66 (continuous), station established in 2018 as partial record site | 10 | Natural | W |

**Table 15.** Continuous-record streamflow-gaging stations and partial-record stations in the surface-water monitoring program for Hawai‘i island, Hawai‘i.—Continued

| Map ID[1] | Status[2] | Operating agency | Station number[3] | Station name[4] or description[5] | Altitude,[6] in feet | Latitude[7] | Longitude[7] | Aspect | Period of record | Years of record[8] | Flow classification | Network[10] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Partial-record stations—Continued | | | | | | | | | | | | |
| P18 | A | USGS | 200517155441801 | Keawewai Stream near Puu Ahia, HI | 4,680 | 20.088 | −155.738 | Leeward | 1963, station established in 2018 as partial record site | 3[9] | Natural | W |
| P19 | A | USGS | 200555155450801 | Waipahoehoe Stream nr Puu Lapalapa, HI | 4,230 | 20.098 | −155.753 | Leeward | 1963, station established in 2018 as partial record site | 3[9] | Natural | W |

[1]Map identification number illustrated in figure 16.

[2]Status of “A” represents an active station as of 2018. Status of “N” represents an additional station needed to supplement the current (2018) program.

[3]Station with a status of “N” that is not a reactivation of an inactive USGS station does not have a station number.

[4]NWIS and CWRM database limitations preclude the use of Hawaiian diacritical marks in station names.

[5]Station with a status of “N” that is not a reactivation of an inactive USGS station does not have a station name; instead, a station description is provided.

[6]Altitude values interpolated from USGS 1:24,000-scale digital hypsography data and rounded to the nearest ten.

[7]Latitude and longitude coordinates in North American Datum of 1983.

[8]For USGS stations, number of years of complete continuous record as of the end of 2018 water year. A water year is a 12-month period that extends from October 1 to September 30 of the following year and is named according to the year during which the period ends. For CWRM stations, an estimate of the number of years of continuous record as of the end of 2018 water year is included.

[9]Number of measurements within the indicated period of record as of May 2019.

[10]A station can be in one or both of the following networks: “C” represents Climate-Response Network. “W” represents Water-Management Network.

The climate-response network for Molokaʻi is represented by eight continuous stations (fig. 13, table 13). Continuous station on Hālawa Stream (C7) is the only continuous station monitoring unregulated flow on the island and has over 90 years of record. Stations on Waihānau Stream (C1), Honoulimaloʻo Stream (C8), Kainalu Gulch (C9), and East Fork Kawela Gulch (C11) were established as part of the 2018 statewide low-flow study and are important for describing streamflow characteristics in the areas with limited hydrologic data. Inactive USGS continuous station on Punaʻula Gulch (C10), with over 20 years of record, is selected for reactivation. Streamflow characteristics in Pelekunu and Pulena Streams (C5 and C6, respectively) were described by data from inactive continuous stations. However, some of the low-flow estimates were poor (Cheng, 2016, table 5) owing to the statistical relations to data at the continuous stations. Therefore, additional monitoring of these streams is needed and stations C5 and C6 are for describing unregulated-flow characteristics in the upper reaches of their respective streams.

Maui's climate-response network is represented by 17 continuous stations (fig. 14–15, table 14). Five of the 14 active stations have a period of record longer than 50 years (C2, C5, C28, C41, and C48), and the station on Honopou Stream (C22) has over 100 years of record. Stations on Ukumehame Gulch (C12), Piʻinaʻau Stream (C40), and Kukuiʻula Gulch (C52) currently monitor low-flow conditions only as they were established as part of the 2018 statewide low-flow study. Piʻinaʻau Stream lies within an under-represented hydrologic setting (see "Setting" for the "Groundwater" section) on Maui, which warrants a continuous station. Hydrologic information in the southeast coast of Maui is scarce; thus, a continuous station on Kukuiʻula Gulch (C52) is selected for the monitoring program. Inactive USGS continuous stations on Kahoma (C19), Haʻipuaʻena (C34), and Nailiilihaele (C28) Streams are considered for reactivation.

The climate-response network for Hawaiʻi island includes nine active continuous stations and four inactive USGS stations selected for reactivation (fig. 16, table 15). Three of the active stations—Kawainui Stream (C3), Alakahi Stream (C4), and Honoliʻi Stream (C8)—have over 50 years of record. Inactive USGS stations on East Branch Honokāne Nui Stream (C2), Wailuku River (C9), Waiākea Stream (C11), and Hīlea Gulch (C13) are selected for reactivation, and stations C11 and C13 have over 20 years of record. Continuous stations for streams just north of Hilo, Hawaiʻi (fig. 1), are selected to represent areas where hydrologic information is scarce. Continuous stations C1, C6, C7, and C15 were established as part of the 2018 statewide low-flow study (fig. 16). During that study, a few observations were made on the streams in the Hāmākua area (fig. 1), and the observations indicated the streams flowed intermittently—mostly during periods of high rainfall. Therefore, no monitoring sites were selected for this area as part of the network.

Seepage-analyses data collection included in the monitoring program are not specific to a data-collection network because results of seepage analyses benefit the goals of both networks. Streams with existing seepage-analysis data as of 2016 are summarized in Cheng (2016, table 1). Additional seepage-analysis data that have been conducted since the publication of that report include Hanapēpē River in Sept. 2017, North Fork Wailuā River in Feb. 2017, and Waikoko Stream in Sept. 2017 on Kauaʻi; Honomuni Gulch in Nov. 2018 on Molokaʻi; Waikapū Stream in Oct. 2018 and May 2019, Kukuiʻula Gulch in June 2019, and Wailuā Stream in July 2019 on Maui; and Kamaʻeʻe Stream in June 2019 on Hawaiʻi island.

A seepage-analysis data collection is identified for streams in surface-water priority areas and streams in hydrogeologically unique areas (table 16, fig. 11–16). The latter generally have a continuous streamflow-gaging station, or a partial-record station selected for the monitoring program. If a stream satisfied these two criteria—it is in a surface-water priority area and hydrogeologically unique area—and has existing seepage-analysis data collected more than 10 years ago, additional seepage-analysis measurements that reflect more recent flow conditions are needed. Streams with established interim instream-flow standards requiring flow releases from diversion intakes (table 8) are also selected for additional seepage-analysis measurements to characterize effects of flow releases on streamflow. Seepage analysis measurements made under various flow conditions can characterize a range of seepage gains and losses. Successive seepage analysis measurements can characterize seepage gain and loss patterns of the stream and could be indicative of localized changes in groundwater levels.

# Groundwater

Groundwater monitoring can involve a collection of many different types of data—from water levels to water quality to water use—over time and space. The objectives of a monitoring program dictate the types of data needed, the methods used to collect them, the duration and frequency of the data collection, and the spatial distribution and number of data-collection sites. The number of sites included in a groundwater-monitoring program is typically constrained by the availability of funding over time. Development of the groundwater-monitoring program described in this report included an analysis of where groundwater monitoring is needed based on current (2018) issues and issues likely to affect groundwater resources in the next two decades, so monitoring can be focused where it likely will be most beneficial.

## Current Groundwater-Resource Issues

Groundwater supplies nearly all drinking water in Hawaiʻi, freshwater for diverse industries, and natural discharge to springs, streams and coasts that supports ecosystems, cultural practices, aesthetics, and recreation. Because the small islands of Hawaiʻi have limited storage capacity, fresh groundwater resources are particularly vulnerable to natural and anthropogenic forces, such as increases in groundwater withdrawal and fluctuations in recharge caused by short- and long-term climate variations. This section of the report discusses issues related to the availability of fresh groundwater for human and ecological uses. The monitoring program does not address water-quality

**Table 16.** Streams included for seepage-analysis discharge measurements in the surface-water monitoring program.

| Kauaʻi | Oahu | Molokaʻi | Maui | | Hawaiʻi |
|---|---|---|---|---|---|
| Hanalei River | Helemano Stream | Hālawa Stream | Alelele Stream | Māliko Gulch | Alakahi Stream |
| Hulēʻia Stream | Kamananui Stream | Honoulimaloʻo Stream | East Wailua Iki Stream | Nailiilihaele Stream | Hakalau Stream |
| Kalalau Stream | Kaukonahua Stream | Kainalu Gulch | Haʻipuaʻena Stream | Nuaʻailua Stream | Hanawī Stream |
| Kapaʻa Stream | Kaupuni Stream | Kaunakakai Gulch | Hāhālawe Gulch | Olowalu Stream | Hīlea Gulch |
| Lāwaʻi Stream | Kawainui Stream | Kawela Gulch | Hanawī Stream | ʻOʻopuola Stream | Honokāne Iki Stream |
| Moloaʻa Stream | Mākaha Stream | Kuhuaʻawi Gulch | Hanehoi Stream | Paʻakea Stream | Honokāne Nui Stream |
| Waiʻalae Stream | Makawao Stream | Punaʻula Gulch | Honokōhau Stream | Palauhulu Stream | Honoliʻi Stream |
| Waimea River | Mālaekahana Stream | Waialua Stream | Honokōwai Stream | Papahawahawa Gulch | Kaʻula Gulch |
| Wainiha River | Mānoa Stream | Waihānau Stream | Honolua Stream | Piʻinaʻau Stream | Kawainui Stream |
| | Maunawili Stream | Waikolu Stream | Honomanū Stream | Puaʻakaʻa Stream | Kaimū Stream |
| | ʻŌpaeʻula Stream | | Honopou Stream | Punalau Stream | Manowaiʻōpae Stream |
| | Poamoho Stream | | Hoʻolawa Stream | Puohokamoa Stream | Umauma Stream |
| | Waiāhole Stream | | Kahoma Stream | Ukumehame Gulch | Waiʻaha Stream |
| | Waiheʻe Stream | | Kailua Stream | Waiaaka Stream | Waiakauaua Gulch |
| | Waikāne Stream | | Kālepalehua Gulch | Waiehu Stream | Waiākea Stream |
| | Waikele Stream | | Kanahā Stream | Waiheʻe River | Waikama Gulch |
| | | | Kapaula Gulch | Waikamoi Stream | Waikoloa Stream |
| | | | Kauaʻula Stream | Waikapū Stream | Wailoa Stream |
| | | | Kaupakulua Gulch | Wailuā Stream | Wailuku River |
| | | | Kahawaipapa Stream | Wailuanui Stream | Waipiʻo Stream |
| | | | Kopiliula Stream | Wailuku River | Waiulili Stream |
| | | | Kukuiʻula Gulch | Waiohue Stream | |
| | | | Launiupoko Stream | Waiokamilo Stream | |
| | | | Makapipi Stream | West Wailua Iki Stream | |

monitoring (except for salinity); issues related to contamination resulting from human activities are not discussed here, even though they can affect groundwater availability.

The 2019 WRPP (State of Hawaiʻi, 2019c) expressed concerns over projected increases in population and consequent increases in demand for drinking water, changing climate, and changing land use, particularly the closure of large sugarcane plantations over the last three decades. Increasing groundwater withdrawals for human use in Hawaiʻi causes lowering of the water table, rise of the transition zone and underlying saltwater, and reductions in natural groundwater discharge to springs, streams, and the ocean (Izuka and others, 2018). Limits placed on these effects—for example, limiting saltwater rise or reductions in natural groundwater discharge—can translate to limits on the availability of groundwater for human use. CWRM seeks to balance water needs for economic growth with water needs to support cultural practices, the environment, and ecosystems in Hawaiʻi (State of Hawaiʻi, 2019c).

CWRM manages groundwater by setting sustainable yield, which Hawaiʻi law defines as "the maximum rate at which water may be withdrawn from a water source without impairing the utility or quality of the water source as determined by the commission" (State of Hawaiʻi, 2019c). Each island in Hawaiʻi is divided into "aquifer systems" (fig. 17), for which sustainable yield generally is computed using an analytical equation based on acceptable changes in water level and the freshwater-saltwater boundary in a freshwater lens for a given estimate of groundwater recharge. CWRM recognizes that the analytical equation has limitations (State of Hawaiʻi, 2019c)—the equation does not account for hydrogeologic variability within an aquifer system and the spatial distribution of production wells; does not consider the effect of groundwater withdrawals on streams, springs, and wetlands; and is not applicable to settings other than the freshwater-lens setting (although inflow from dike-impounded-groundwater and perched-groundwater settings within an aquifer system can be included in the groundwater flowing through that system's freshwater lens). The 2019 WRPP (State of Hawaiʻi, 2019c) recognizes that aquifer-system boundaries were established with limited subsurface information and do not necessarily constitute hydrologic boundaries. Given these limitations, CWRM places greater management scrutiny on aquifer systems when actual or allocated withdrawals approach or exceed estimated sustainable yields, and it considers interactions between groundwater and surface water during well-permit evaluations (State of Hawaiʻi, 2019c).

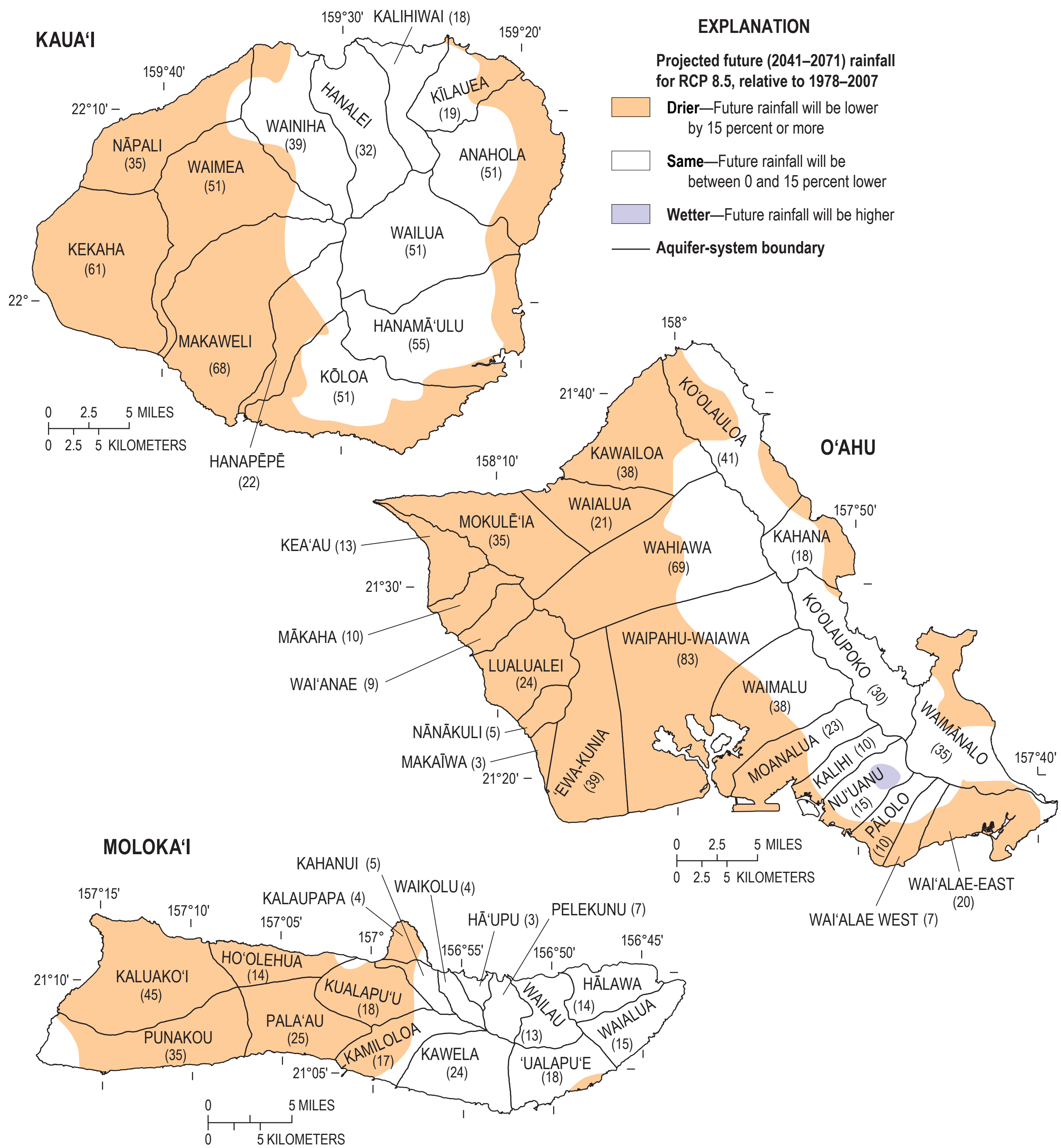



**Figure 17.** Maps showing the aquifer systems used by the State of Hawai‘i Commission on Water Resource Management to manage groundwater resources for the Hawaiian Islands of Kaua‘i, O‘ahu, Moloka‘i, Maui, Lāna‘i, and Hawai‘i, superimposed on projections for rainfall change for mid-century (2041–2071). Area in square miles given in parentheses. Rainfall projections are from statistical downscaling by Elison Timm and others (2015) for representative concentration pathway (RCP) 8.5 from the Intergovernmental Panel on Climate Change. Aquifer system boundaries are from State of Hawai‘i (2008b).

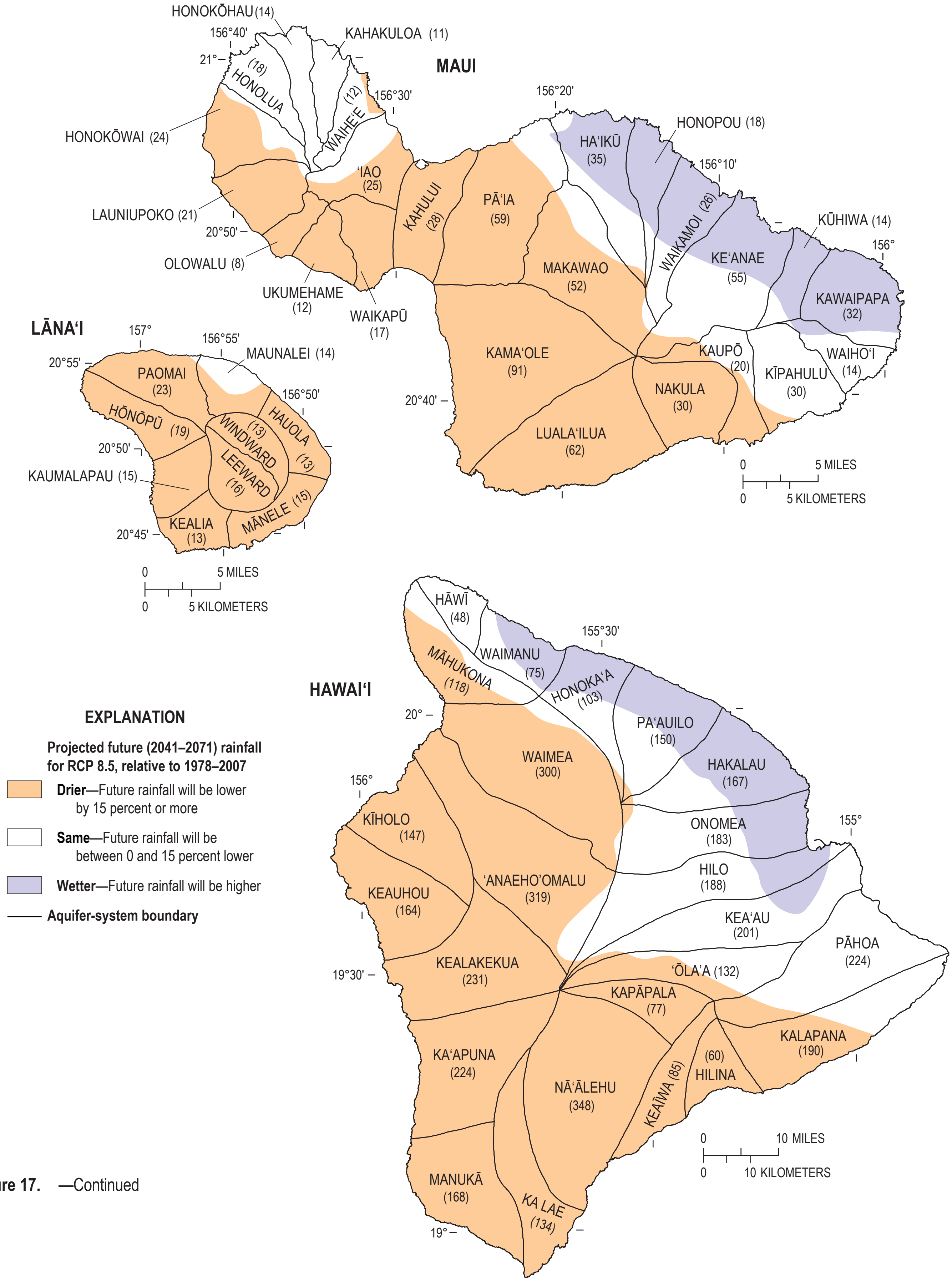



**Figure 17.** —Continued

As discussed in the "Setting" section of this report, some enigmatic groundwater occurrences in Hawaiʻi do not fit into one of the four principal settings (freshwater-lens, dike-impounded-groundwater, thickly saturated, and perched-groundwater settings). Because hydrogeologic conditions responsible for these enigmatic occurrences are not completely understood, effects of groundwater development and their implications for groundwater availability may be difficult to assess.

Reduction in the amount of water that recharges Hawaiʻi's aquifers caused by climate and land-cover changes may further constrain the amount of water available for human use. Precipitation data indicate a long-term drying trend in Hawaiʻi over the last century (Kruk and Levinson, 2008; Chu and others, 2010); concurrent declines in groundwater discharge to streams is evident in some Hawaiʻi streams (Oki, 2004; Bassiouni and Oki, 2013). Statistical downscaling of results from general circulation models indicates that rainfall in some areas of Hawaiʻi will decrease in the future (Elison Timm and others, 2015; fig. 17), and these decreases could reduce future groundwater recharge (Mair and others, 2019). Changes in land use can affect groundwater recharge because different land covers can have different rates of evaporation and different effects on the balance of water in the soil (Engott and Vana, 2007; Engott, 2011; Izuka and others, 2018). Agricultural irrigation, in particular, can have a substantial effect on groundwater recharge, but the net effect on groundwater resources differs depending on the source of the irrigation water. If crops are irrigated with stream water that would normally have run off to the ocean, irrigation can enhance groundwater recharge (Izuka and others, 2005) and have a net positive effect on groundwater resources. On the other hand, if crops are irrigated with groundwater, irrigation exposes the water to additional evapotranspiration and runoff losses, so the net effect on groundwater resources is negative.

The 2019 WRPP (State of Hawaiʻi, 2019c) recognized that monitoring sites in the current groundwater-monitoring program are inequitably distributed and that the sites can be better distributed to improve spatial coverage. Oʻahu has the largest groundwater withdrawal and the most monitoring sites, but the number of sites on an island is not necessarily commensurate with withdrawal. Not all hydrologic settings are equitably monitored, even though factors limiting groundwater availability differ among the settings (Izuka and others, 2018).

## Data-Collection Strategies

The groundwater-resource monitoring program focuses on the collection of water-level and salinity data in monitoring wells. These data provide information on changes in the fresh-groundwater storage that may result from groundwater withdrawals or changes in recharge related to changes in climate or land use. Water levels measured in wells are fundamental datasets that have implications for all aspects of groundwater assessments, including quantifying and tracking changes in storage and evaluating the direction and rates of groundwater flow and contaminant transport. Salinity data can indicate movement of the freshwater-saltwater transition zone, which relates to changes in the size of freshwater lenses. Strategies for evaluating the status of or changes in groundwater resources in an area include: (1) long-term water-level monitoring, (2) specific-conductance profiles through the transition zone, and (3) synoptic water-level surveys.

### Long-Term Water-Level Monitoring

Long-term water-level monitoring consists of regular measurements of groundwater at the same set of representative wells over periods of several years—ideally multiple decades—because the full effect of withdrawal from a new well can take decades to develop. Long-term water-level monitoring data are essential for assessing the effect of withdrawal on groundwater storage and for identifying how groundwater resources respond to multi-year climate cycles and gradual climate change. Long-term water-level monitoring is useful for all of the hydrogeologic settings discussed above.

Two methods for acquiring long-term water-level data are (1) continuous monitoring and (2) discrete measurements. At continuous-monitoring sites, electronic instruments automatically record water levels at frequent intervals, typically several times per hour. The sites are also visited by field personnel about once every 3 to 4 months to maintain equipment and make manual measurements. Automated collection of frequent water-level data collected over a long period provides data for determining short-term variations (for example, those that result from tides, withdrawals from nearby wells, or recharge pulses) and long-term trends. Also, most continuous-monitoring sites can be accessed remotely and can provide data in near real time.

At discrete-measurement sites, water levels are measured manually once every 1 to 6 months. Data from discrete-measurement sites can indicate long-term trends and long-period cycles but may not be able to resolve short-period fluctuations. Depending on the interval between measurements, monitoring using the discrete-measurement method may not show medium-period (for example, seasonal) fluctuations. Operating costs for discrete-measurement sites are usually less than for continuous-monitoring sites, except when field visits are more frequent than about six times per year. Most monitoring programs will use a combination of continuous-monitoring and discrete-measurement sites to achieve a balance between data-frequency needs and wide distribution within cost limits.

### Specific-Conductance Profiles through the Transition Zone

Specific conductance (more precisely, fluid specific electrical conductance) is a water-salinity indicator. A specific-conductance profile is the measurement of specific-electrical conductance, typically with an electronic probe, with depth in the water column of a deep monitor well (DMW) that penetrates through the transition zone (fig. 18). Specific conductance in the transition zone ranges from that of freshwater above to seawater below. The transition zone can move and change thickness in response to changes in withdrawal and recharge.

Specific-conductance profiles through the freshwater-saltwater transition zone provide important information in freshwater-lens settings. The 2019 WRPP (State of Hawai‘i, 2019c) recommends a “mauka-to-makai” (inland to coast) distribution of specific-conductance profiling sites to monitor different parts of each freshwater lens. Periodic specific-conductance profiles can show changes in the thickness of the lens or transition zone and indicate impending saltwater encroachment to important production wells.

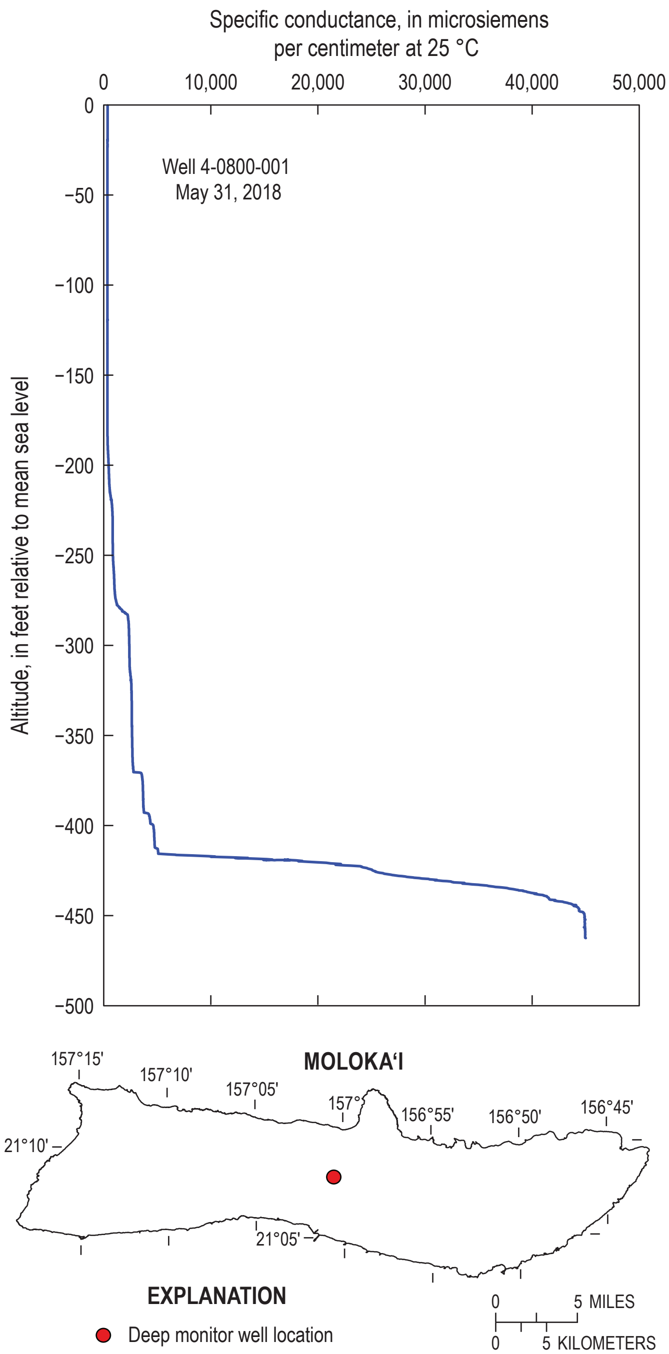



**Figure 18.** Diagram showing an example of a specific-conductance profile from deep monitor well 4-0800-001 on Moloka‘i, Hawai‘i. Data from U.S. Geological Survey (2019).

Specific-conductance profiling sites are much fewer than long-term water-level sites. Specific-conductance profiles are of limited value in most dike-impounded-groundwater or thickly saturated settings, where the transition zone, if it exists, is at great depths not likely to limit groundwater availability. Only in a few places is the transition zone in a dike-impounded-groundwater setting shallow enough to warrant specific-conductance profiling. Specific-conductance profiles are irrelevant in perched-groundwater settings because the groundwater body is not immediately underlain by saltwater. The cost of specific-conductance profiling sites also limits their number and measurement frequency. Specific-conductance profiling usually requires a deep well constructed specifically for the purpose, whereas long-term water-level sites commonly can use shallower or existing wells. Procedures for specific-conductance profiling also typically take more time than those for water-level measurements. However, specific-conductance profiling sites can be considered part of the long-term water-level monitoring effort because manual water-level measurements are normally part of the profiling procedures.

A specific-conductance probe may also be positioned at a specified depth, typically near or within the transition zone, in the well to collect continuous specific-conductance data between field visits. Although this type of monitoring does not provide as much information on the structure of the transition zone as profiling does, it provides a more continuous record of specific-conductance variations with time. Multiple, closely spaced, fixed-depth specific-conductance probes positioned within the transition zone can approximate a continuous record of the structure of the transition zone.

## Synoptic Water-Level Surveys

A synoptic water-level survey is the simultaneous (or nearly simultaneous) measurement of water levels at as many widely spaced wells as practical in a region of interest (fig. 19). Whereas long-term water-level monitoring tracks temporal changes at selected sites, synoptic surveys provide more information on spatial distribution of water levels within the region for an instant in time. Repeating a synoptic survey every few years, combined with long-term water-level monitoring of selected wells in the interim, provides a comprehensive picture of the variation of a region’s water level in space and time.

Synoptic water-level surveys are useful for monitoring a freshwater-lens setting, where the water table is areally extensive, continuous, and has a measurable gradient (fig. 4*A* and 4*B*). Synoptic surveys may have limited utility in highly compartmentalized aquifers, such as in dike-impounded-groundwater settings; in aquifers where the water table may have very little gradient, such as the high-altitude water table beneath central O‘ahu; or where the groundwater body has limited extent, such as in perched-groundwater settings. A given synoptic survey typically covers an area with a continuous water table. A single synoptic survey may span more than one aquifer system, because not all aquifer-system boundaries correspond to hydrogeologic barriers.

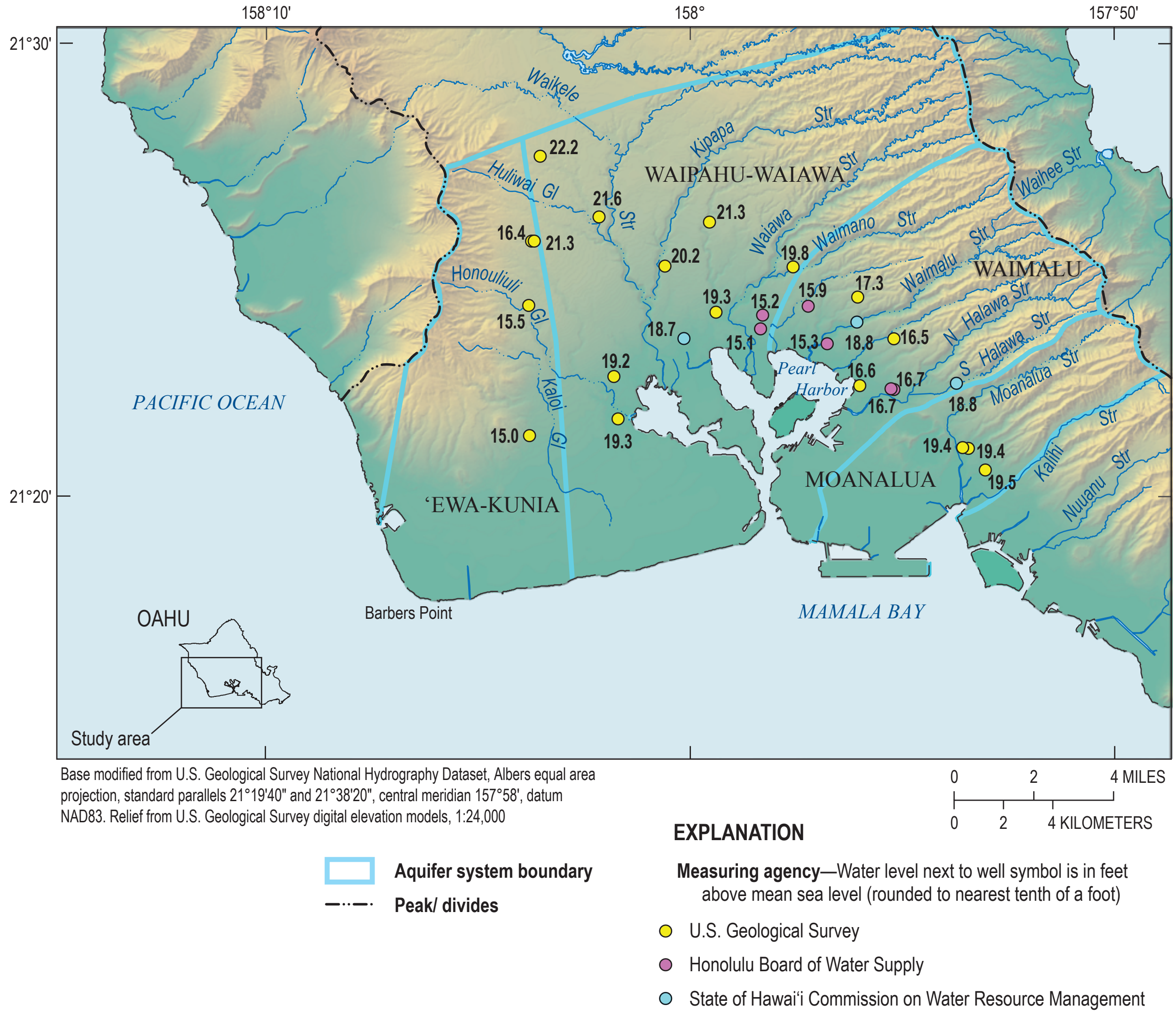



**Figure 19.** Map showing a synoptic water-level survey on O‘ahu, Hawai‘i, April 26, 2012, 9:00 a.m. to 11:45 a.m. Modified from U.S. Geological Survey (2013a).

Ideally, all wells within a given synoptic survey would be measured at precisely the same time, but in practice, a survey measures as many wells as possible in as short a time span as possible (about two hours). Thus, synoptic surveys are necessarily opportunistic—they are most practical in areas where a sufficient number of accessible wells already exists and are distributed over the entire area of interest. In the monitoring program, surveys are identified only for areas that have a sufficient number of potentially measurable wells.

Surveys may require coordination of large field crews, possibly from multiple agencies, which places practical limits on the frequency at which a survey can be repeated and on the areal extent a single synoptic survey can cover. For practical reasons, a large survey may be divided into subsurveys. Alternatively, water levels could be measured at fewer selected sites, balancing the need for data density (water levels per unit area) with the need to synoptically survey an entire hydrologically continuous region. The required spatial data density for a given synoptic survey depends on how much water levels vary in horizontal space—which depends on hydrogeology, pumping distribution, and other conditions.

Synoptic surveys can use automated water-level recorders in lieu of manual measurements. This reduces the need for large field crews for large synoptic surveys but incurs costs for instruments and additional labor for installation. A combination of manual and automated recorders can be used to make large surveys feasible within time and funding constraints. The use of automated recorders also improves the ability to achieve measurement simultaneity that is critical in areas where water-levels fluctuate substantially and rapidly, such as in high-permeability aquifers near the coast where water levels are influenced by ocean tides. The recorders can be programmed to make measurements automatically at specified times; water levels used in a synoptic-survey analysis can be selected from the measurements taken at a specified time by all the recorders deployed for the survey.

Synoptic surveys are not currently part of a regularly scheduled monitoring plan, although the USGS has conducted synoptic surveys in Hawaiʻi as part of short-term hydrologic investigations (for example, Gingerich 2008). The 2019 WRPP recommends that synoptic surveys "should be conducted at least twice a year in all important areas" (State of Hawaiʻi, 2019c) to capture variability between wet and dry seasons.

### Monitoring-Well Characteristics

The characteristics of wells used for groundwater monitoring can affect the data that come from them and some analyses that require comparison of data from multiple wells. To mitigate the cost of constructing new monitor wells, groundwater-monitoring methods described in this report can use wells that already exist, but some key aspects of the wells must be known, and included in metadata, to ensure that the objectives of the monitoring program discussed in this report are met. Aspects of well construction—depth of well boring, casing, open intervals, and packing in the annular space between the rock bore and casing—can affect the water levels and specific-conductance profiles in a well. The water level in a given well is an integration of the heads over the open interval of the well, and salinities in the well may partially adjust to the integrated head. As a result, well construction can affect how representative the water level and salinity profiles in a well are to conditions in the aquifer, especially in settings where vertical head gradients are steep. The proximity of a monitor well to production wells can also affect the utility of the data. The closer a monitor well is to a pumped well, the more the data from the monitor well will be dominated by the local effects of the pumped well, which may not be representative of the hydrologic conditions of the region.

## Groundwater-Monitoring Program

The groundwater-monitoring program considered groundwater-monitoring priority based on two major objectives: (1) management of groundwater resources, and (2) assessing the response of aquifers to climate changes. These objectives are generally consistent with those in a review of the USGS groundwater data-collection program in Hawaiʻi in the 1990s (Anthony, 1997). These objectives are a key consideration when choosing monitoring stations and effective monitoring methods.

*Resource Management.*—Resource management utilizes data from monitoring of conditions that are indicative of groundwater-development effects. These conditions include the altitude and slope of the water table and the depth and shape of the freshwater-saltwater transition zone underlying freshwater lenses (effects on groundwater discharge to streams are monitored by stream gages, as discussed earlier in this report). Monitoring is most useful when measurements are made over extended periods because rates and spatial distribution of withdrawals change with time. Also, aquifers typically respond to these changes gradually—some effects can take decades to fully develop, depending on the magnitude of change and characteristics of the aquifer. Because monitoring for the resource-management objective seeks to track effects of groundwater development, monitoring ideally uses wells that are influenced by groundwater withdrawals at the regional scale, that is, within the area of pumping influence of a region of wells, but not so near an individual pumped well that the data are dominated by that well. Water levels monitored in pumped wells for operational purposes can, in some cases, provide information useful for resource management, but they may offer limited information on the regional water table. A water level measured in a well while the pump is operating includes well losses, which are partly influenced by well construction and other factors specific to the well, not the regional aquifer. Specific-conductance profiles in DMWs near pumped wells can be affected by borehole flows induced by the pumped well (Rotzoll, 2012).

*Climate Response.*—The availability of fresh groundwater for human use is also affected by fluctuations in climate. Because precipitation is the ultimate source of all fresh groundwater in the islands of Hawaiʻi, changes in precipitation can alter groundwater storage and, in turn, groundwater availability. The climate-response objective seeks to monitor effects from climate-related stresses, such as droughts and long-term climate change. These effects will vary from one hydrogeologic setting to another. In dike-impounded-groundwater settings where groundwater is compartmentalized into relatively small units of storage, small changes in recharge can have large effects on water levels. In freshwater-lens settings, effects are spread over the larger volume of the lens but include effects from above (at the water table) and below (at the transition zone). A comprehensive network for the climate-response objective requires monitoring sites in areas that represent the various combinations of climate and hydrogeologic settings in Hawaiʻi; however, ideal monitoring sites for the climate-response objective would be located far from areas of groundwater withdrawal (outside the area of influence of any pumped well) and away from significant land-use changes that can alter groundwater recharge.

### Resource-Management Network

The groundwater-monitoring program used CWRM's aquifer systems (fig. 17) as a framework for determining the resource-management network. The first step of the assessment process was the identification of aquifer systems with the highest priority for groundwater monitoring on the basis of several criteria established through collaboration with CWRM:

1. **High withdrawal.** Current or anticipated withdrawal rates in the aquifer system are high relative to sustainable yields established by CWRM.

2. **Declining storage.** Declining fresh groundwater storage, as indicated by declining water levels and (or) rising salinity, is a concern in the aquifer system.

3. **Effects on flows to the surface or adjacent aquifers.** Concerns that withdrawals from the aquifer system will reduce flow to streams, coasts, or adjacent aquifers.

4. **Recharge reduction.** Concerns exist that changes in land use or climate may reduce recharge in the aquifer system. Climate-change concern was based on whether the aquifer system encompasses areas where rainfall is projected to decrease by 15 percent or more relative to current average rainfall. The rainfall projection is based on statistical downscaling of general-circulation-model simulations of representative concentration pathway (RCP) 8.5 mid-century (2041–2071) by Elison Timm and others (2015; fig. 17).

5. **Critical resource.** The aquifer system is critical to population or industry centers that have no alternative sources.

6. **Hydrogeologic uncertainties.** Uncertainties about the hydrogeology of the aquifer system limit the ability to assess the availability of fresh groundwater.

Other criteria that may be unique to a particular aquifer system were also considered during discussions with CWRM and other stakeholders, such as the County of Kaua‘i Department of Water, the HBWS, the County of Maui Department of Water Supply (MDWS), and the County of Hawai‘i Department of Water Supply (HDWS). Aquifer systems that were identified as having a need for groundwater monitoring were placed into one of three priority categories—high, medium, or low; some aquifer systems were not prioritized if none of the above criteria applied to them.

The second step in the assessment process was to compare the priority areas to the current groundwater-monitoring program. This step helped assess how well the current program met the identified priorities. For the purposes of the monitoring program, only sites monitored by the USGS, CWRM, and the HBWS were considered part of the current program; however, no common data-quality plan has been adopted by all three agencies in Hawai‘i (see additional discussion in the “Data-Quality Objectives” section).

The third step in the assessment was the identification of modifications to the current program to meet priorities. In general, high-priority aquifer systems were considered to require a higher density of monitoring sites to facilitate effective management of groundwater resources; medium- and low-priority aquifer systems were considered to require fewer sites. However, the number of sites and the monitoring methods needed also depend on geologic structures, hydrologic settings, and microclimates encompassed within the area of an aquifer system. In the monitoring program, additional monitoring sites that supplement the current program are selected with consideration of the groundwater-monitoring priority and locations of active monitoring sites. The locations of the additional sites are general, that is, nearby sites may equally meet monitoring objectives. Final site selection requires consideration of multiple practical issues, such as cost, site accessibility, and the availability of existing usable wells, especially if those wells already have historical data.

### Kaua‘i

Kaua‘i has 13 aquifer systems, 6 of which were identified as high priority for groundwater monitoring (fig. 20). Parts of all six aquifer systems include areas where projections indicate possible decreases in future rainfall (fig. 17). Four of the aquifer systems—Kīlauea, Anahola, Wailuā, and Hanamā‘ulu—have thickly saturated settings, where the effect of groundwater withdrawals on streams may limit groundwater availability. The Hanamā‘ulu aquifer system also is an area where declining water levels have been a concern (Izuka, 2006). In the Kōloa aquifer system, concerns exist about changing land use and future rises in salinity. The coastal plain of the Kekaha aquifer system has undergone recent changes in land use and groundwater withdrawal, related to the closure of sugarcane plantations, that are anticipated to affect groundwater levels.

Kalihiwai is the only aquifer system on Kaua‘i identified as having a medium priority for groundwater monitoring. The presence of thickly saturated settings in eastern Kaua‘i raises the possibility that groundwater-withdrawal effects on streams will limit groundwater availability. The Wainiha, Hanapēpē, and Makaweli aquifer systems were identified as having a low priority for groundwater monitoring; parts of these aquifer systems include areas where rainfall may decrease in the future (fig. 17), but none of the other criteria apply to them.

### Long-Term Water-Level Monitoring

Long-term water levels are currently monitored at 15 sites on Kaua‘i (fig. 20, table 17). Most active sites are in the population and industry centers of east and south Kaua‘i, but two sites are in the less-populated north. Most of the high-priority aquifer systems currently have long-term water-level monitoring sites, but some have only one or two active sites, and one (Kīlauea) has no active sites. Kauai’s medium-priority aquifer system (Kalihiwai) has no active long-term water-level monitoring sites. The three low-priority aquifer systems each have at least one active long-term water-level monitoring site, but the site in the Makaweli aquifer system is near its eastern border and less than a mile from the site in the adjacent Hanapēpē aquifer system.

Broad areas within priority aquifer systems on Kaua‘i are not being monitored currently for long-term water levels. To address this lack of data, 25 additional sites on Kaua‘i are selected for long-term water-level monitoring (fig. 20). High-priority aquifer systems have at least three long-term water-level monitoring sites, and in most instances, these include sites from inland to nearshore parts of the aquifer systems. The exception is in the Kekaha aquifer system, where the focus of additional sites is on groundwater concerns in the coastal plain; additional sites extend monitoring to the northwestern part of the coastal plain that currently is not monitored. The medium-priority Kalihiwai aquifer system has two additional sites to monitor inland and coastal areas. The low-priority aquifer systems each have at least one active or additional long-term water-level monitoring site. An additional monitoring site is selected for the Makaweli aquifer system to monitor farther from the border than the active site.

## Specific-Conductance Profiling

Most of the island consists of dike-impounded-groundwater and thickly saturated settings (fig. 4), where specific-conductance profiles have limited value because the deep transition zone is unlikely to limit fresh-groundwater availability. Areas on Kaua‘i that warrant specific-conductance profiling are along the southern coast where freshwater-lens settings exist. Five additional specific-conductance monitoring sites are selected in this part of the island (fig. 21). The sites are in high-priority aquifer systems and are positioned to monitor nearshore and inland parts of the freshwater lenses. No additional sites are selected for the two low-priority aquifer systems along the southern shore of Kaua‘i.

## Synoptic Water-Level Surveys

Two synoptic water-level surveys are needed for Kaua‘i (fig. 22). The south Kaua‘i synoptic survey is intended to monitor changes in the water-table configuration of the freshwater-lens settings in the high-priority Kekaha and Kōloa aquifer systems and the intervening low-priority Makaweli and Hanapēpē aquifer systems. The east Kaua‘i synoptic survey is intended to monitor changes in the thickly saturated settings in the high-priority Kīlauea, Anahola, Wailua, and Hanamā‘ulu aquifer systems and the thickly saturated setting of the medium-priority Kalihiwai aquifer system. The east Kaua‘i synoptic survey is large, however, and measuring all of the potentially usable wells in the short

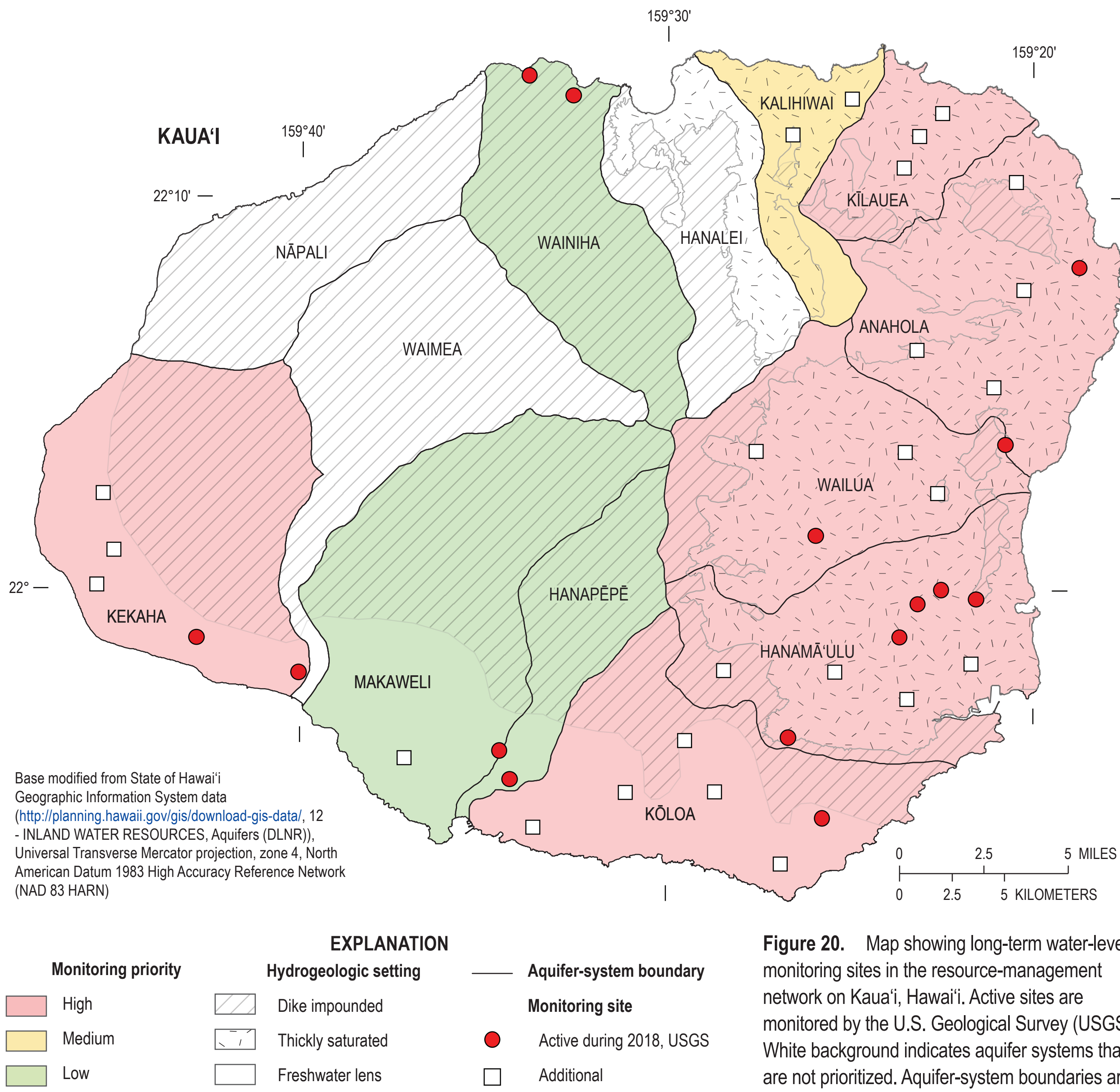



**Figure 20.** Map showing long-term water-level monitoring sites in the resource-management network on Kaua‘i, Hawai‘i. Active sites are monitored by the U.S. Geological Survey (USGS). White background indicates aquifer systems that are not prioritized. Aquifer-system boundaries are from State of Hawai‘i (2008b). Hydrogeologic-setting extents are from Izuka and others (2018).

**Table 17.** Active groundwater sites for resource management by the State of Hawaiʻi Commission on Water Resource Management (CWRM), the U.S. Geological Survey (USGS), and the Honolulu Board of Water Supply (HBWS) on Kauaʻi, Oʻahu, Molokaʻi, Lānaʻi, Maui, and Hawaiʻi island, Hawaiʻi.

[Names are from the CWRM's well database, except where indicated. Sources for first-year-of-data column: for wells monitored by USGS, dates are for data in NWIS, although earlier data may exist that is not in NWIS; for wells monitored by CWRM, dates are from Patrick Casey (CWRM, written commun., August 2019) or NWIS, whichever is earlier; for wells monitored by HBWS, dates are from Nancy Matusmoto (HBWS, written commun., September 2019) or NWIS, whichever is earlier; other data may exist that are not in NWIS; gaps in data may exist between date shown and present. LTW, long-term water-level; SCP, specific-conductance profiling]

| State number | Type | Name | Aquifer system | Agency | First year of data |
|---|---|---|---|---|---|
| | | Kauaʻi | | | |
| 2-0022-001 | LTW | Hanamaulu 1 | Hanamāʻulu | USGS | 1994 |
| 2-0126-001 | LTW[1] | NW Kilohana Mon | Wailua | USGS | 1996 |
| 2-0320-003 | LTW | Nonou 9-1B | Anahola | USGS | 1970 |
| 2-0818-003 | LTW | Anahola 3 | Anahola | USGS | 1991 |
| 2-1232-001 | LTW | Wainiha 1 | Wainiha | USGS | 1962 |
| 2-1333-001 | LTW | Haena | Wainiha | USGS | 1965 |
| 2-5425-015 | LTW | Koloa F | Kōloa | USGS | 2017 |
| 2-5534-003 | LTW | Hanapepe 1 | Hanapēpē | USGS | 1966 |
| 2-5626-001 | LTW | Puakukui Springs | Hanamāʻulu | USGS | 1995 |
| 2-5634-001 | LTW | Hanapepe Ridge | Makaweli | USGS | 1961 |
| 2-5840-001 | LTW | Waimea A | Kekaha | USGS | 1966 |
| 2-5843-001 | LTW | Kekaha Shaft 12 | Kekaha | USGS | 1948 |
| 2-5921-001 | LTW | Kalepa Ridge | Hanamāʻulu | USGS | 1954 |
| 2-5923-001 | LTW | Kilohana A | Hanamāʻulu | USGS | 1973 |
| 2-5923-008 | LTW | Hanamaulu TZ | Hanamāʻulu | USGS | 1995 |
| | | Oʻahu | | | |
| 3-1647-004 | LTW | Kaimuki A | Waiʻalae-West | CWRM | 2001 |
| 3-1747-004 | SCP | Waialae SH Deep Monitor | Waiʻalae-West | HBWS | 1996 |
| 3-1748-012 | LTW | Keanu | Pālolo | HBWS | 1986 |
| 3-1748-014 | SCP | Kaimuki Sta Deep Monitor | Pālolo | HBWS | 1986 |
| 3-1749-022 | SCP | Kaimuki HS Deep Monitor | Pālolo | HBWS | 1972 |
| 3-1848-001 | SCP | Waahila Deep Monitor | Pālolo | HBWS | 1999 |
| 3-1851-002 | LTW | Thomas Square | Nuʻuanu | HBWS | 1925 |
| 3-1851-019 | LTW | Halekauwila St (Pipe A and B) | Nuʻuanu | USGS | 1973 |
| 3-1851-057 | SCP | Beretania Deep Monitor | Nuʻuanu | HBWS | 1968 |
| 3-1952-048 | SCP | Kalihi Sta Deep Monitor | Kalihi | HBWS | 2000 |
| 3-2052-010 | LTW | Kapalama | Kalihi | HBWS | 1959 |
| 3-2052-012 | SCP | Jonathan Springs | Kalihi | HBWS | 1981 |
| 3-2053-010 | LTW | Fort Shafter Monitor | Moanalua | USGS | 1915 |
| 3-2101-003 | LTW | Honouliuli | Waipahu-Waiawa | USGS | 1910 |
| 3-2153-005 | SCP | Moanalua Deep Monitor | Moanalua | HBWS | 2002 |
| 3-2153-008 | LTW | TAMC 2 | Moanalua | USGS | 1945 |
| 3-2153-009 | LTW | Moanalua-Manaiki | Moanalua | HBWS | 1945 |
| 3-2153-013 | LTW | TAMC MW-2 | Moanalua | USGS | 2015 |
| 3-2201-010 | SCP | Kunia T41 Deep Monitor | Waipahu-Waiawa | HBWS | 2000 |
| 3-2253-003 | SCP | Halawa Deep Monitor Well | Waimalu | CWRM | 2000 |
| 3-2255-033 | LTW | Halawa Obs. T45 | Waimalu | HBWS | 1954 |

**Table 17.** Active groundwater sites for resource management by the State of Hawaiʻi Commission on Water Resource Management (CWRM), the U.S. Geological Survey (USGS), and the Honolulu Board of Water Supply (HBWS) on Kauaʻi, Oʻahu, Molokaʻi, Lānaʻi, Maui, and Hawaiʻi island, Hawaiʻi.—Continued

| State number | Type | Name | Aquifer system | Agency | First year of data |
|---|---|---|---|---|---|
| Oʻahu—Continued | | | | | |
| 3-2255-040 | SCP | Halawa Deep Monitor[2] | Waimalu | HBWS | 1996 |
| 3-2256-010 | LTW | FW 1 | Waimalu | USGS | 1935 |
| 3-2300-018 | SCP | Waipahu Deep Monitor Well | Waipahu-Waiawa | CWRM, HBWS | 1986 |
| 3-2355-015 | SCP | Kaamilo Deep Monitor | Waimalu | HBWS | 2001 |
| 3-2356-057 | LTW | Waimalu | Waimalu | HBWS | 1990 |
| 3-2358-020 | LTW | Pearl City Obs T-27 | Waipahu-Waiawa | HBWS | 1946 |
| 3-2403-002 | SCP | Kunia Middle Deep Monitor Well | ʻEwa-Kunia | CWRM | 2002 |
| 3-2449-002 | LTW | Windward Oahu Ex | Koʻolaupoko | CWRM, HBWS | 2000 |
| 3-2455-001 | LTW | Upper Waimalu T52 | Waimalu | HBWS | 1956 |
| 3-2456-004 | SCP | Newtown Deep Monitor | Waimalu | HBWS | 2000 |
| 3-2456-005 | SCP | Waimalu Deep Monitor Well | Waimalu | CWRM | 2005 |
| 3-2458-006 | SCP | Manana Deep Monitor | Waipahu-Waiawa | HBWS | 2000 |
| 3-2459-026 | SCP | Waiawa Deep Monitor | Waipahu-Waiawa | HBWS | 2001 |
| 3-2503-003 | SCP | Kunia Mauka Deep Monitor Well | ʻEwa-Kunia | CWRM | 2004 |
| 3-2557-004 | SCP | Waimano Deep Monitor | Waipahu-Waiawa | HBWS | 2002 |
| 3-2602-002 | SCP | Poliwai Deep Monitor | Waipahu-Waiawa | HBWS | 2001 |
| 3-2659-001 | SCP | Waipio Mauka Deep Monitor Well | Waipahu-Waiawa | CWRM, HBWS | 1985 |
| 3-2703-002 | LTW | Kunia Basal Monitor | Waipahu-Waiawa | CWRM | 1997 |
| 3-2901-002[3] | LTW | Schofield | Wahiawā | USGS | 1966 |
| 3-3405-005 | SCP | Helemano Deep Monitor | Waialua | HBWS | 2002 |
| 3-3406-004 | LTW | Waialua | Waialua | HBWS | 1986 |
| 3-3409-016 | LTW | Mokuleia | Mokulēʻia | CWRM | 1924 |
| 3-3410-008 | LTW | Mokuleia | Mokulēʻia | CWRM | 1929 |
| 3-3553-005 | SCP | Punaluu Deep Monitor | Koʻolauloa | HBWS | 1968 |
| 3-3554-005 | LTW | Kaluanui 2 Monitor | Koʻolauloa | HBWS | 2003 |
| 3-3604-001 | SCP | Kawailoa Deep Monitor | Kawailoa | HBWS | 1995 |
| 3-3755-010 | SCP | Hauula Deep Monitor | Koʻolauloa | HBWS | 2001 |
| 3-3956-008 | SCP | Laie Deep Monitor | Koʻolauloa | HBWS | 2004 |
| 3-4057-017 | SCP | Kahuku Deep Monitor | Koʻolauloa | HBWS | 2003 |
| 3-4059-001 | LTW | Kahuku TVWF 2011 | Koʻolauloa | USGS | 2012 |
| Molokaʻi | | | | | |
| 4-0449-001 | LTW | Ualapue Shaft | ʻUalapuʻe | USGS | 1947 |
| None | LTW[1] | Kaunakakai | Kamiloloa | USGS | 1954 |
| 4-0800-001 | SCP | Kualapuu Deep Monitor | Kualapuʻu | USGS | 2001 |
| Maui | | | | | |
| 6-4225-001 | LTW | Maui Meadows | Kamaʻole | CWRM | 2006 |
| 6-4422-001 | LTW | Waiohuli | Kamaʻole | CWRM | 2001 |
| 6-4824-001 | LTW | Kihei Exploratory | Pāʻia | CWRM | 1972 |
| 6-4831-001 | LTW | Maalaea 272 | Waikapū | CWRM | 1965 |
| 6-5130-001 | LTW | Waikapu 1 | ʻĪao | CWRM | 1961 |

**Table 17.** Active groundwater sites for resource management by the State of Hawai‘i Commission on Water Resource Management (CWRM), the U.S. Geological Survey (USGS), and the Honolulu Board of Water Supply (HBWS) on Kaua‘i, O‘ahu, Moloka‘i, Lāna‘i, Maui, and Hawai‘i island, Hawai‘i.—Continued

| State number | Type | Name | Aquifer system | Agency | First year of data |
|---|---|---|---|---|---|
| Maui—Continued | | | | | |
| 6-5130-002 | LTW | Waikapu 2 | ‘Īao | USGS | 1974 |
| 6-5230-002 | SCP | Iao Deep Monitor Well | ‘Īao | CWRM | 2006 |
| 6-5430-005 | SCP | Waiehu Deep Monitor | ‘Īao | USGS, CWRM | 1983 |
| 6-5431-001 | LTW | Waiehu TH-B | ‘Īao | USGS | 1974 |
| 6-5631-009 | SCP | Waihee Deep Monitor Well | Waihe‘e | CWRM | 2011 |
| 6-5731-005 | LTW | Kanoa TH | Waihe‘e | USGS | 2001 |
| 6-5739-003 | SCP | Mahinahina Deep Monitor Well | Honokōwai | CWRM | 2001 |
| Hawai‘i | | | | | |
| 8-0437-001 | LTW[1] | Waiohinu Exploratory | Nā‘ālehu | USGS | 1997 |
| 8-3155-001 | LTW | Kealakekua[2] | Kealakekua | CWRM | 1991 |
| 8-3255-002 | LTW | Kainaliu | Kealakekua/Keauhou | CWRM | 1993 |
| 8-3355-002 | LTW | Keauhou Kam 2 | Keauhou | CWRM | 1991 |
| 8-3457-002 | LTW | Keauhou A | Keauhou | CWRM | 1985 |
| 8-3457-004 | SCP | Kahaluu | Keauhou | CWRM | 2000 |
| 8-3657-002 | LTW | Pahoehoe | Keauhou | CWRM | 1990 |
| 8-3858-001 | SCP | Keopu 1 Deep Monitor Well | Keauhou | CWRM | 2001 |
| 8-3858-002 | LTW | Keopu 2 Deep Monitor Well | Keauhou | CWRM | 2017 |
| 8-3957-002 | LTW | Komo[2] | Keauhou | CWRM | 1991 |
| 8-3957-004 | LTW | Keopu DC1[2] | Keauhou | CWRM | 2001 |
| 8-4061-001 | LTW | Kaho 1 | Keauhou | USGS | 1995 |
| 8-4161-001 | LTW | Kaho 3 | Keauhou | USGS | 1996 |
| 8-4161-002 | LTW | Kaho 2 | Keauhou | USGS | 1996 |
| 8-4360-001 | LTW | Kalaoa N Kona | Keauhou | CWRM | 1968 |
| 8-5347-001 | LTW | Puu Anahulu | ‘Anaeho‘omalu | CWRM | 1996 |
| 8-6046-001 | LTW | Ouli 1 | Waimea | CWRM | 1989 |
| 8-6141-001 | LTW | USGS Waiaka Tank | Māhukona | CWRM | 1999 |
| 8-6144-001 | LTW | Kanehoa | Māhukona | CWRM | 2005 |
| 8-6145-001 | LTW | Ouli[2] | Māhukona | CWRM | 2013 |
| 8-6147-001 | LTW | Kawaihae 3 | Māhukona | CWRM | 1963 |

[1] Also part of climate-response network

[2] Differs from the name in the CWRM well database

[3] Data from this well may be listed under well number 03-2901-007 in previous reports

period of a synoptic survey may be problematic. The east Kaua‘i synoptic survey can be made more feasible with the advance deployment of recorders on some wells or choosing fewer wells to measure while maintaining adequate data density. Another option, although less ideal, is to divide the east Kaua‘i synoptic survey into north and south subsurveys; but the subsurveys should have some wells in common to facilitate comparisons.

Synoptic surveys are of limited value, elsewhere on Kaua‘i, where the dike-impounded-groundwater setting predominates. In this setting, groundwater is compartmentalized by low-permeability structures, and the water table is discontinuous.

### O‘ahu

O‘ahu has 23 aquifer systems, 12 of which were identified as high priority for groundwater monitoring on the basis of multiple criteria (fig. 23). All but one of these aquifer systems have high totals for existing and allocated withdrawal rates relative to CWRM estimates of sustainable yields, and parts of most of

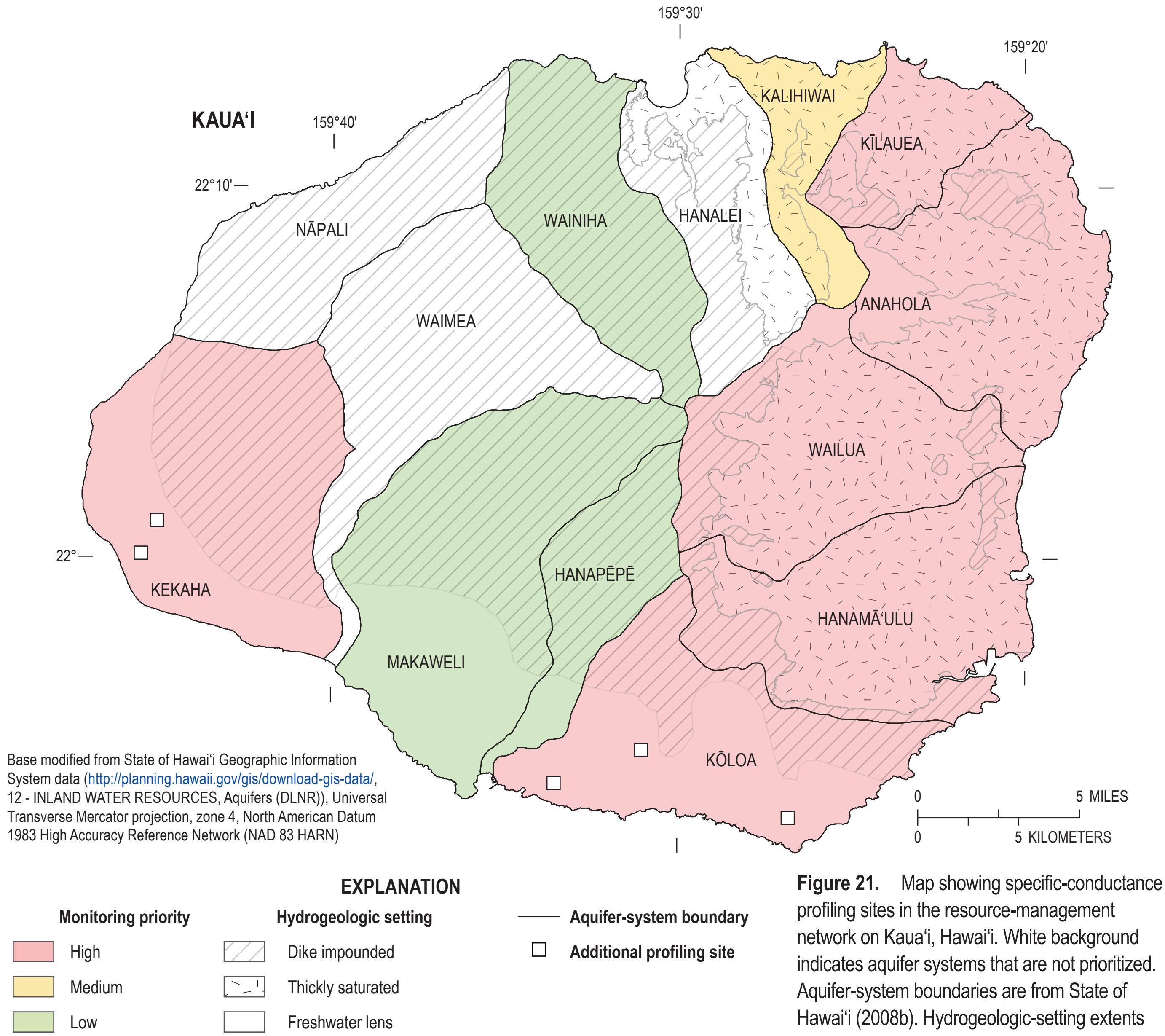



**Figure 21.** Map showing specific-conductance profiling sites in the resource-management network on Kaua'i, Hawai'i. White background indicates aquifer systems that are not prioritized. Aquifer-system boundaries are from State of Hawai'i (2008b). Hydrogeologic-setting extents are from Izuka and others (2018).

the aquifer systems include areas where projections indicate that rainfall may decrease in the future (fig. 17). Additional criteria that support the high-priority identification of these aquifer systems include concerns about effects on streams or coastal discharge (Mākaha, Wai'anae, 'Ewa-Kunia, and Waipahu-Waiawā,), rising salinity ('Ewa-Kunia, Waimalu, Kalihi, Nu'uanu, and Pālolo,), uncertain boundaries between aquifer systems (Waimalu and Moanalua), concerns about effects on or from adjacent aquifers possible in the future ('Ewa-Kunia), and the aquifer systems are critical sources with no alternatives (Mākaha and Wai'anae). Additionally, the Wahiawā aquifer system is important because groundwater from the Wahiawā aquifer system flows to other aquifer systems, including the heavily developed Waipahu-Waiawa aquifer system, yet it includes the enigmatic Schofield high-level groundwater. Withdrawals in the Ko'olaupoko aquifer system are not high, but concerns have been raised about effects on streams, and the HBWS considers this aquifer system among those of primary concern (HBWS, oral commun., 2018).

Eight aquifer systems on O'ahu were identified as having medium priority for groundwater monitoring. Parts of each of these aquifer systems include areas where projections indicate that rainfall may decrease in the future (fig. 17). Additional criteria that support medium priority include potential future concerns about effects on streams (Kahana and Waimānalo, which have substantial dike-impounded-groundwater settings), potential future concerns about reduced inflows from adjacent aquifers and uncertain aquifer-system boundaries (Mokulē'ia and Waialua), and aquifer systems are critical sources with no alternatives (Mokulē'ia). Two aquifer systems were identified as low priority for groundwater monitoring because of concerns about projected reductions in future rainfall.

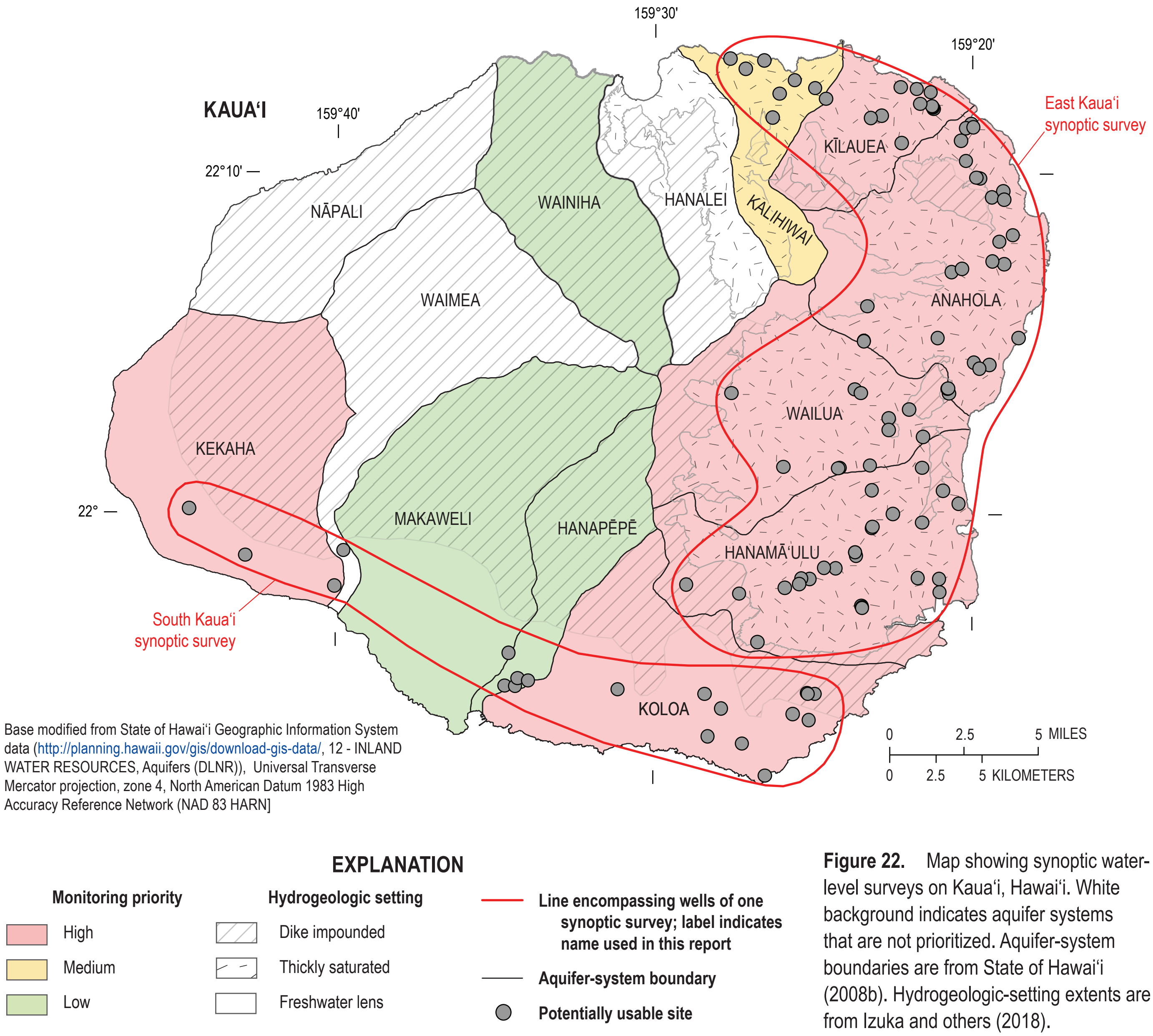



**Figure 22.** Map showing synoptic water-level surveys on Kaua‘i, Hawai‘i. White background indicates aquifer systems that are not prioritized. Aquifer-system boundaries are from State of Hawai‘i (2008b). Hydrogeologic-setting extents are from Izuka and others (2018).

## Long-Term Water Levels

O‘ahu has half of all the long-term water-level sites that are currently monitored in Hawai‘i, which is consistent with the island’s population (fig. 23, table 17). Of the 51 active sites, 38 are distributed in Honolulu and near Pearl Harbor, including the highly productive and high-priority Waipahu-Waiawa, Waimalu, Moanalua, Kalihi, Nu‘uanu, Pālolo, and Wai‘alae-West aquifer systems. Water levels in these aquifer systems historically have fluctuated with variations in withdrawal rates and recharge from irrigation (State of Hawai‘i, 2019c). The other active long-term water-level sites are scattered among aquifer systems of medium- to low-priority ranking. Two aquifer systems (Wai‘anae and Makaha) identified as high priority have no active sites, whereas some lesser-priority aquifer systems have as many as five active sites.

The resource-management network includes 55 additional long-term water-level monitoring sites to improve the correspondence with the priority ranking (fig. 23, table 17). The additional sites include 22 sites selected by the Pearl Harbor Monitoring Working Group (PHMWG), which was assembled by CWRM in 2001 to develop a groundwater monitoring plan for the critically important and highly productive aquifer systems in the Pearl Harbor area. An additional 33 sites are selected in this study to cover areas not addressed by the PHMWG.

The need for long-term water-level monitoring places at least three sites in each high-priority aquifer system, with more sites in some aquifer systems consistent with their size and importance as sources of drinking water. At least two sites are in each of the medium-priority aquifer systems, except for the Nānākuli and Makaīwa aquifer systems, which are small. At least one additional site is needed in each low-priority aquifer system.

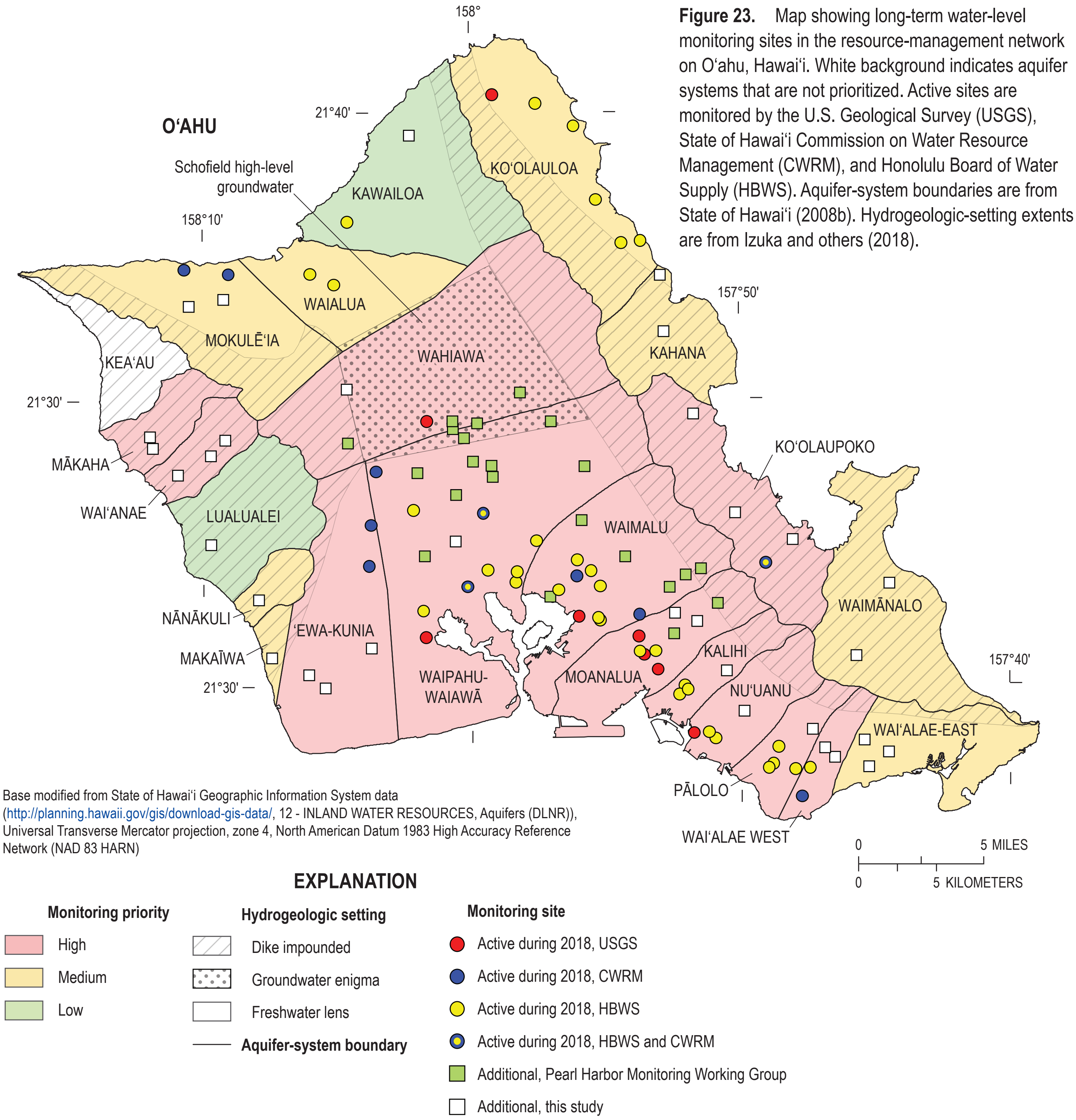



**Figure 23.** Map showing long-term water-level monitoring sites in the resource-management network on O‘ahu, Hawai‘i. White background indicates aquifer systems that are not prioritized. Active sites are monitored by the U.S. Geological Survey (USGS), State of Hawai‘i Commission on Water Resource Management (CWRM), and Honolulu Board of Water Supply (HBWS). Aquifer-system boundaries are from State of Hawai‘i (2008b). Hydrogeologic-setting extents are from Izuka and others (2018).

## Specific-Conductance Profiling

O‘ahu has 28 active sites monitored for specific conductance, (fig. 24, table 17). All high-priority aquifer systems on O‘ahu with freshwater-lens settings have at least one active specific-conductance profiling site; some have multiple sites, particularly the heavily developed aquifer systems near Pearl Harbor and Honolulu. Some aquifer systems that have been identified as medium priority (Ko‘olauloa and Waialua) and low priority (Kawailoa) also have active sites that are monitored for specific conductance. Many of the remaining aquifer systems (including high- and medium-priority systems) encompass dike-impounded-groundwater settings or enigmatic high-level-groundwater settings that do not warrant specific-conductance profiling, except possibly in coastal areas.

The monitoring program includes 16 additional specific-conductance profiling sites to supplement the current program (fig. 24). Seven of the additional sites were selected by the PHMWG; six monitor the inland extents, and one monitors the

coastal part of the freshwater-lens setting in the Waipahu-Waiawa and Waimalu aquifer systems surrounding Pearl Harbor. This study places additional sites in areas to achieve consistency with the aquifer-system priority assessment for the groundwater-monitoring program. Additional sites for the high-priority ‘Ewa-Kunia, Moanalua, Kalihi, Nu‘uanu and Wai‘alae-West aquifer systems complement active sites to create transects from inland to the coastal parts of the freshwater-lens setting. One additional specific-conductance profiling site is placed in the freshwater-lens settings in each of the medium-priority Mokulē‘ia and Wai‘alae-East aquifer systems. Additional sites are also placed in the heavily developed, high-priority Mākaha and Wai‘anae aquifer systems, but because these aquifer systems encompass areas that are intruded by dikes, specific-conductance profiling is needed only near the coast where saltwater may be shallow enough to affect fresh-groundwater availability. The high-priority Ko‘olaupoko and medium-priority Kahana and Waimānalo aquifer systems also encompass dike-impounded-groundwater settings, but withdrawals are not a large enough fraction of their sustainable yields to warrant specific-conductance profiling. No specific-conductance profiling is warranted for the high-priority Wahiawā aquifer system because the system is mostly covered by the Schofield high-level groundwater, where saltwater intrusion is not likely to limit fresh groundwater availability.

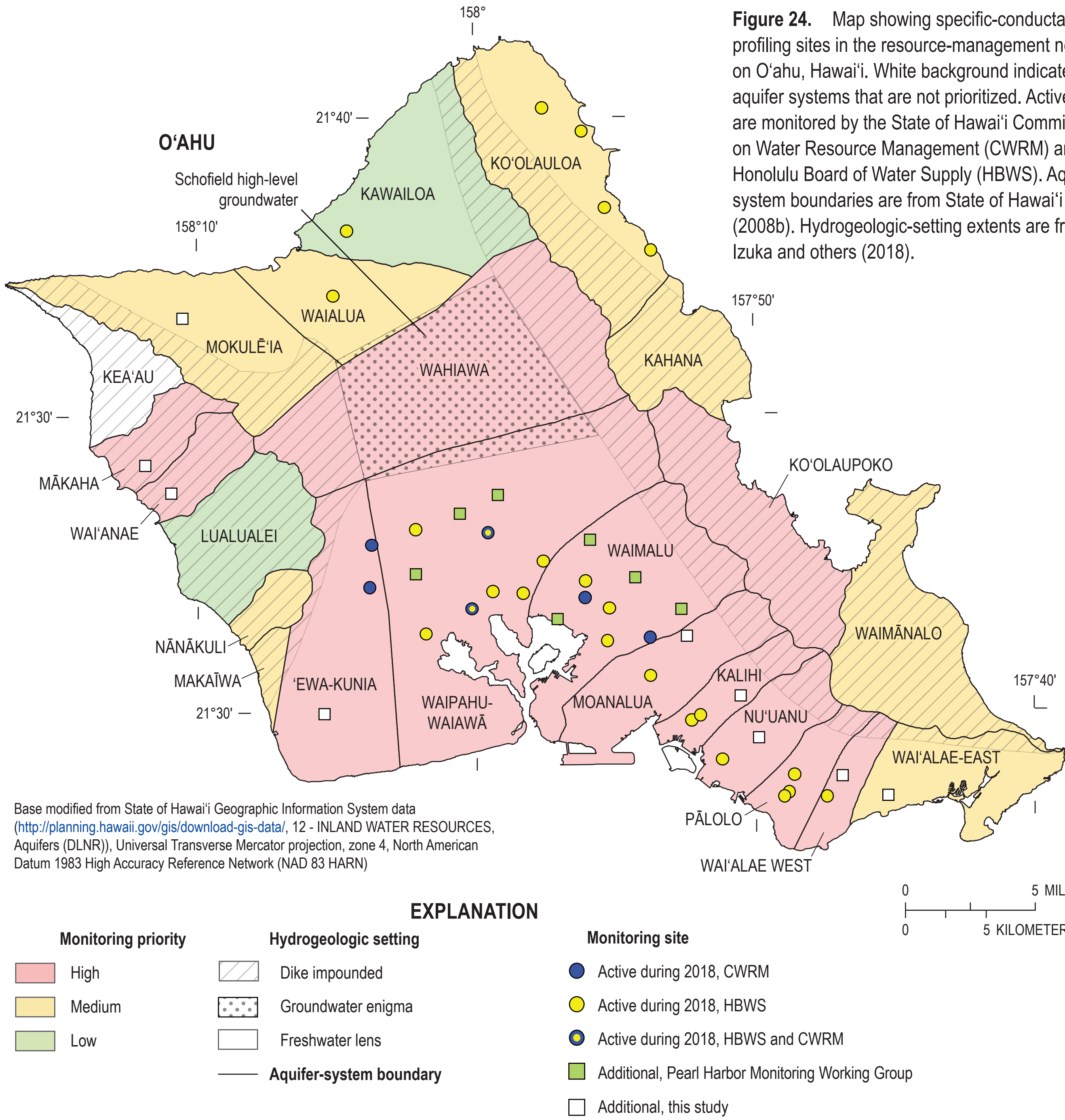



**Figure 24.** Map showing specific-conductance profiling sites in the resource-management network on O‘ahu, Hawai‘i. White background indicates aquifer systems that are not prioritized. Active sites are monitored by the State of Hawai‘i Commission on Water Resource Management (CWRM) and Honolulu Board of Water Supply (HBWS). Aquifer-system boundaries are from State of Hawai‘i (2008b). Hydrogeologic-setting extents are from Izuka and others (2018).

## Synoptic Water-Level Surveys

Three synoptic water-level surveys are needed on O‘ahu (fig. 25). The south O‘ahu synoptic survey includes an area near Pearl Harbor that has been surveyed before (USGS, 2013a) but extends into the adjacent highly-developed freshwater lenses in Honolulu to the east. The south O‘ahu synoptic survey includes more than a hundred wells that could potentially be measured, but doing so in the short period allowed for a synoptic survey may be problematic unless fewer wells are selected for measurement while still achieving adequate data density, or some wells are measured using recorders deployed in advance. A less-ideal alternative is to divide the south O‘ahu synoptic survey into east and west subsurveys that could be measured at different times, but some wells should be part of both subsurveys so that comparisons can be made.

The north O‘ahu and Ko‘olauloa synoptic surveys are intended to monitor changes in the freshwater-lens settings of the medium- to low-priority aquifer systems in these areas. Other areas of O‘ahu, including some high-priority aquifer systems, are in settings where synoptic surveys would have limited utility because water levels are compartmentalized by dikes or have little spatial variation.

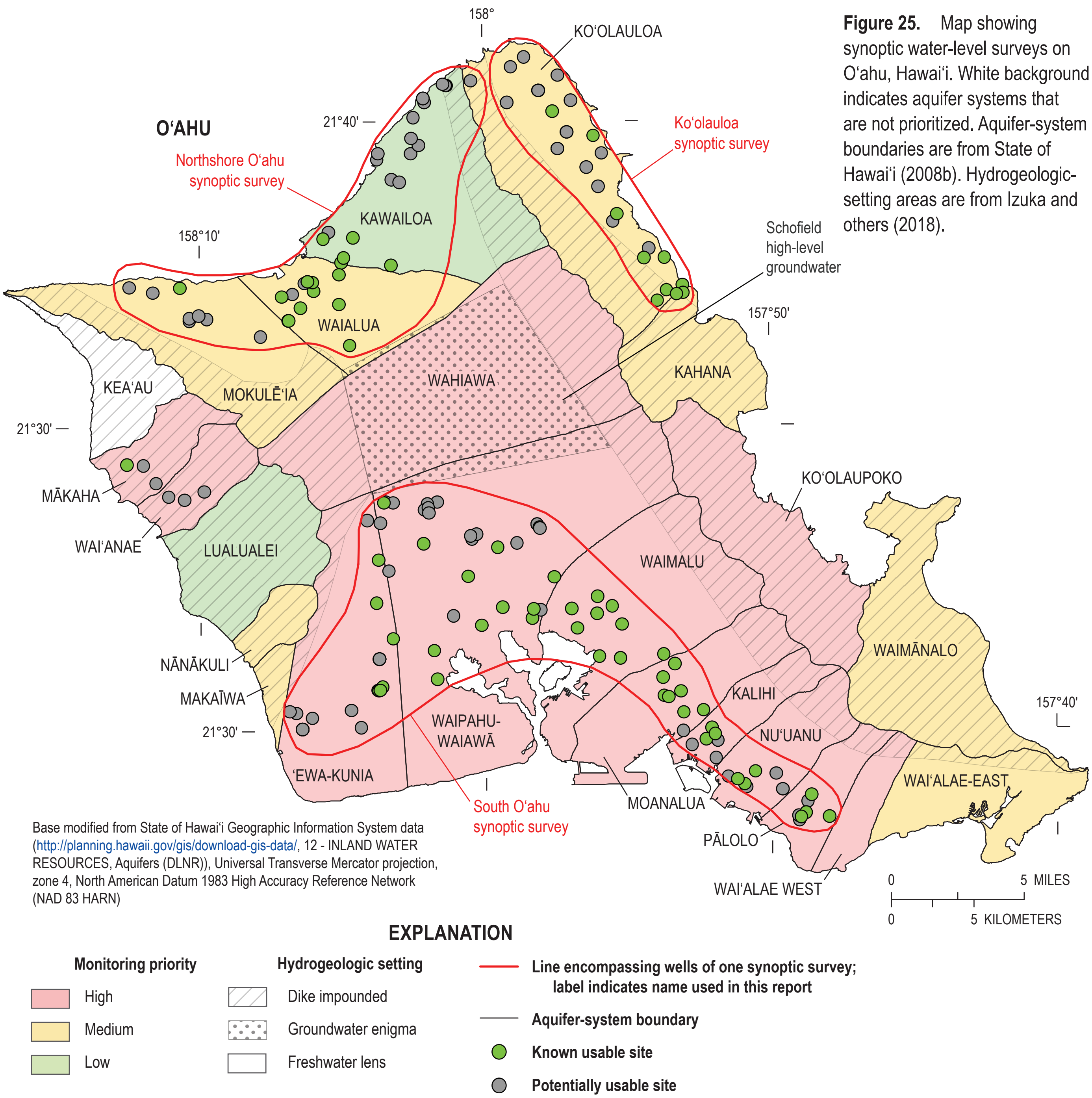



**Figure 25.** Map showing synoptic water-level surveys on O‘ahu, Hawai‘i. White background indicates aquifer systems that are not prioritized. Aquifer-system boundaries are from State of Hawai‘i (2008b). Hydrogeologic-setting areas are from Izuka and others (2018).

## Moloka‘i

Moloka‘i has 16 aquifer systems, 6 of which were identified as needing groundwater monitoring (fig. 26). The Kualapu‘u aquifer system was identified as high priority because it is an important source of water for Moloka‘i’s population; and it has relatively high current and anticipated withdrawal rates, whose effect on costal discharge and flows to adjacent aquifers are concerns. Also, much of the aquifer system is in the area where projections indicate a potential decrease in rainfall (fig. 17). Three aquifer systems were identified as medium priority for various reasons, including moderately high pumping rates relative to sustainable yields (Pala‘au); concerns about effects on streamflow and coastal discharge or future declines in storage (Kamiloloa and Kawela); and effects from climate change (Pala‘au and Kamiloloa). Two aquifer systems (Waikolu and ‘Ualapu‘e) were identified as low priority.

### Long-Term Water-Level Monitoring

Long-term water level is monitored at three active sites on Moloka‘i (fig. 26, table 17). One site is in the single high-priority Kualapu‘u aquifer system, one site is in the medium-priority Kamiloloa aquifer system, and one site is in the low-priority ‘Ualapu‘e aquifer system. Other aquifer systems that have been identified as needing groundwater monitoring have no active long-term water-level sites. To improve long-term water level monitoring relative to the resource-management priorities, eight additional monitoring sites are selected for Moloka‘i (fig. 26). Two additional sites are in the high-priority Kualapu‘u aquifer system—one site is in the north of the aquifer system, and the other site is an additional specific-conductance profiling site. Additional long-term water-level monitoring sites are included in the medium-priority aquifer systems, so each has two sites. In the Pala‘au and Kamiloloa aquifer systems, the sites are positioned so that inland and coastal parts of each aquifer system could be monitored. In the Kawela aquifer system, one of the additional sites is a well with previous data, and the other is a specific-conductance profiling site. One site is included in each of the low-priority aquifer systems.

### Specific-Conductance Profiling

Specific-conductance profiling is being conducted at one active DMW in the Kualapu‘u aquifer system on Moloka‘i (fig. 27, table 17). Although the site is in a dike-impounded-groundwater setting where the transition zone is commonly deep, geophysical data indicate that the transition zone shallows toward the southwest (Oki, 2000). Data collected during the drilling of the DMW indicated that the well penetrated through the transition zone and into groundwater that was near the salinity of seawater (Oki and Bauer, 2001). Four additional DMWs for specific-conductance profiling are selected for Moloka‘i, one in each of the high- and medium-priority aquifer systems. The active and additional DMWs in the high-priority Kualapu‘u aquifer system and medium-priority Kamiloloa and Kawela aquifer systems form a transect from central Moloka‘i to the coast, including a part of the Kualapu‘u aquifer system that is an area of possible future groundwater development (Oki, 2000).

### Synoptic Water-Level Surveys

One synoptic water-level survey is needed for Moloka‘i (fig. 28). The survey is intended to monitor changes in the

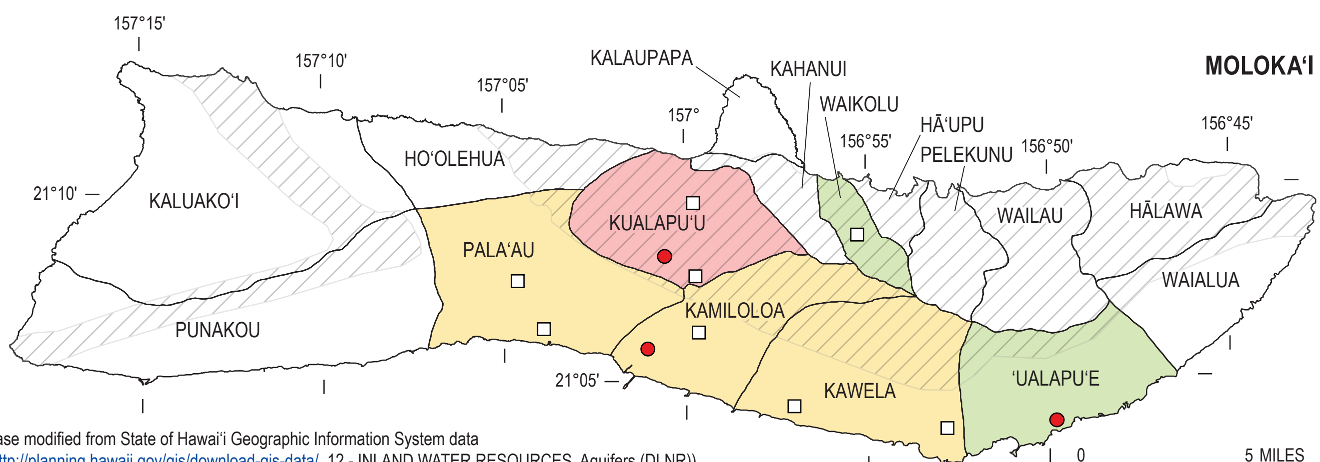
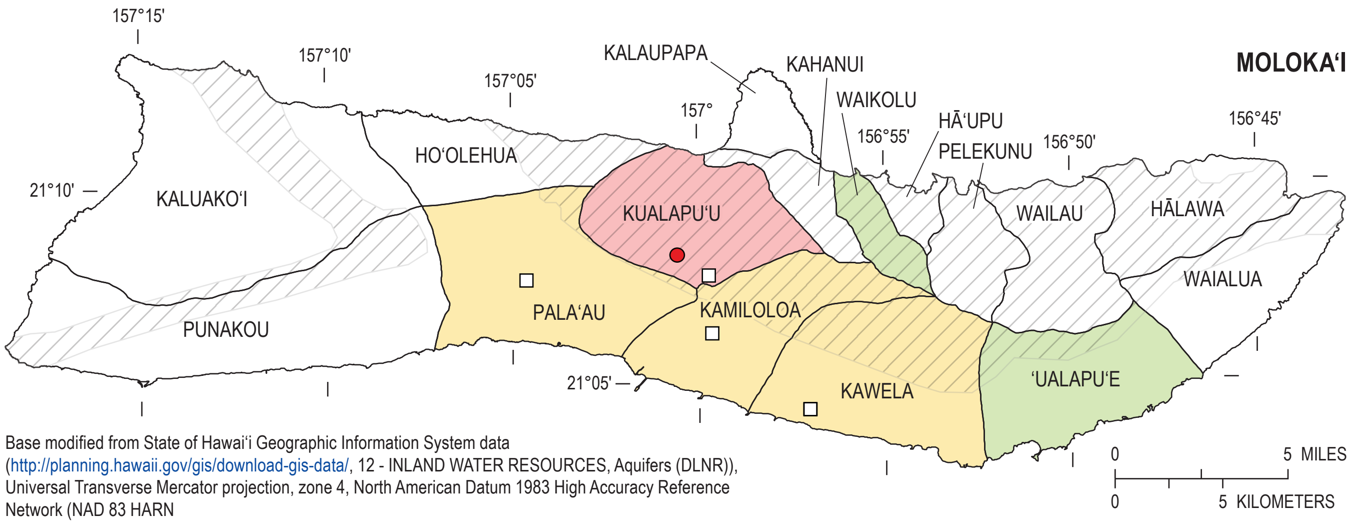



**Figure 26.** Map showing long-term water-level monitoring sites in the resource-management network on Moloka‘i, Hawai‘i. White background indicates aquifer systems that are not prioritized. Active sites are monitored by the U.S. Geological Survey (USGS). Aquifer-system boundaries are from State of Hawai‘i (2008b). Extent of dike-impounded-groundwater setting is based on Oki (1997).



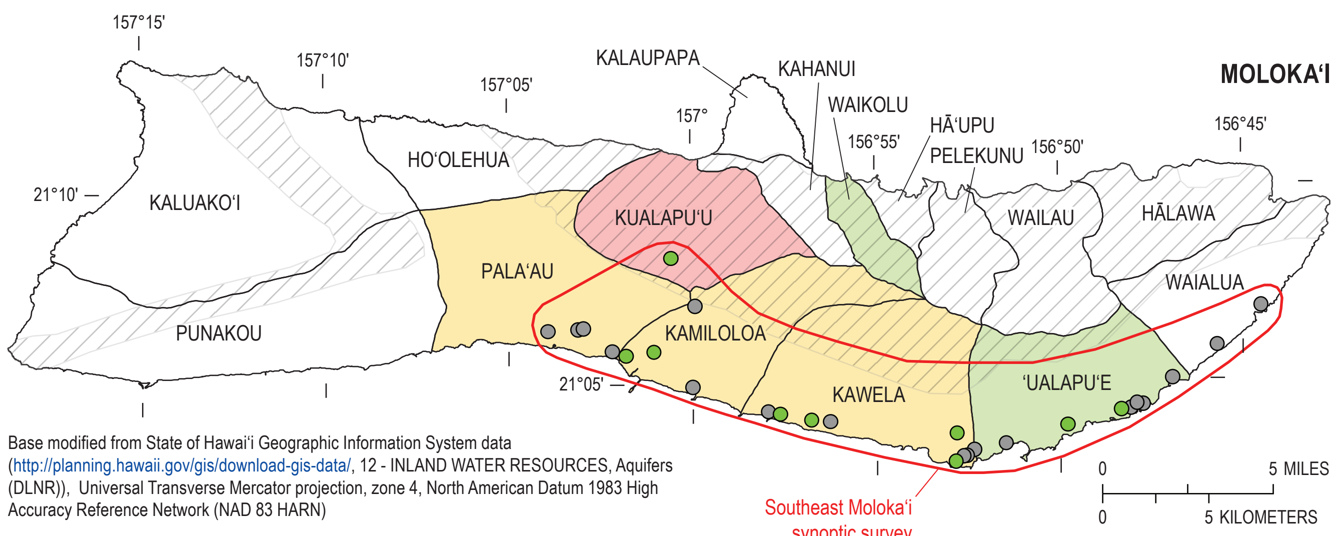

EXPLANATION

**Monitoring priority**
- High
- Medium
- Low

**Hydrogeologic setting**
- Dike impounded
- Freshwater lens
- **Aquifer-system boundary**

**Monitoring site**
- Active during 2018, USGS
- Additional

**Figure 27.** Map showing specific-conductance profiling sites in the resource-management network on Moloka'i, Hawai'i. White background indicates aquifer systems that are not prioritized. Active site is monitored by the U.S. Geological Survey (USGS). Aquifer-system boundaries are from State of Hawai'i (2008b). Extent of dike-impounded-groundwater setting is based on Oki (1997).




EXPLANATION

**Monitoring priority**
- High
- Medium
- Low

**Hydrogeologic setting**
- Dike impounded
- Freshwater lens

- **Line encompassing wells of one synoptic survey; label indicates name used in this report**
- **Aquifer-system boundary**
- **Known usable site**
- **Potentially usable site**

**Figure 28.** Map showing synoptic water-level surveys on Moloka'i, Hawai'i. White background indicates aquifer systems that are not prioritized. Aquifer-system boundaries are from State of Hawai'i (2008b). Extent of dike-impounded-groundwater setting is based on Oki (1997).

configuration of the water table of the freshwater-lens settings in the medium- and low-priority aquifer systems along the south-eastern coast, and the survey extends northward into the dike-impounded-groundwater setting of the high-priority Kualapu'u aquifer system. The synoptic survey also extends to the east to include potentially usable wells in the nonprioritized Waialua aquifer system, which has a water table that is probably continuous with the rest of the survey area.

## Lāna‘i

Lāna‘i has nine aquifer systems, all of which include areas where projections indicate a possible decrease in rainfall (fig. 17). Most of these aquifer systems, however, have little or no groundwater development; thus, they were not prioritized in terms of groundwater-monitoring need. The Windward and Leeward aquifer systems in the center of the island were identified as having a high priority for groundwater monitoring because they provide water to most of the island's small resident population of about 3,000 (U.S. Census Bureau, 2011).

No long-term groundwater monitoring sites are active on Lāna‘i. Six additional sites are needed for long-term monitoring to supplement the current program, three sites in each of the high-priority Windward and Leeward aquifer systems (fig. 29). No specific-conductance profiling is currently conducted on Lāna‘i or included in the monitoring program described in this report. No synoptic water-level surveys are included for Lāna‘i because few wells are available for potential use, and synoptic surveys would have limited value in the discontinuous, compartmentalized water tables in the dike-impounded-groundwater setting.

## Maui

Maui has 25 aquifer systems, 9 of which were identified as high priority for groundwater monitoring (fig. 30). Most of these aquifer systems were identified as high priority because multiple criteria pertained to them, including high withdrawal (Waihe‘e, ‘Īao, Honokōwai, and Kahului), declining-storage concerns (Waihe‘e, ‘Īao, Honokōwai, and Kahului), concerns about

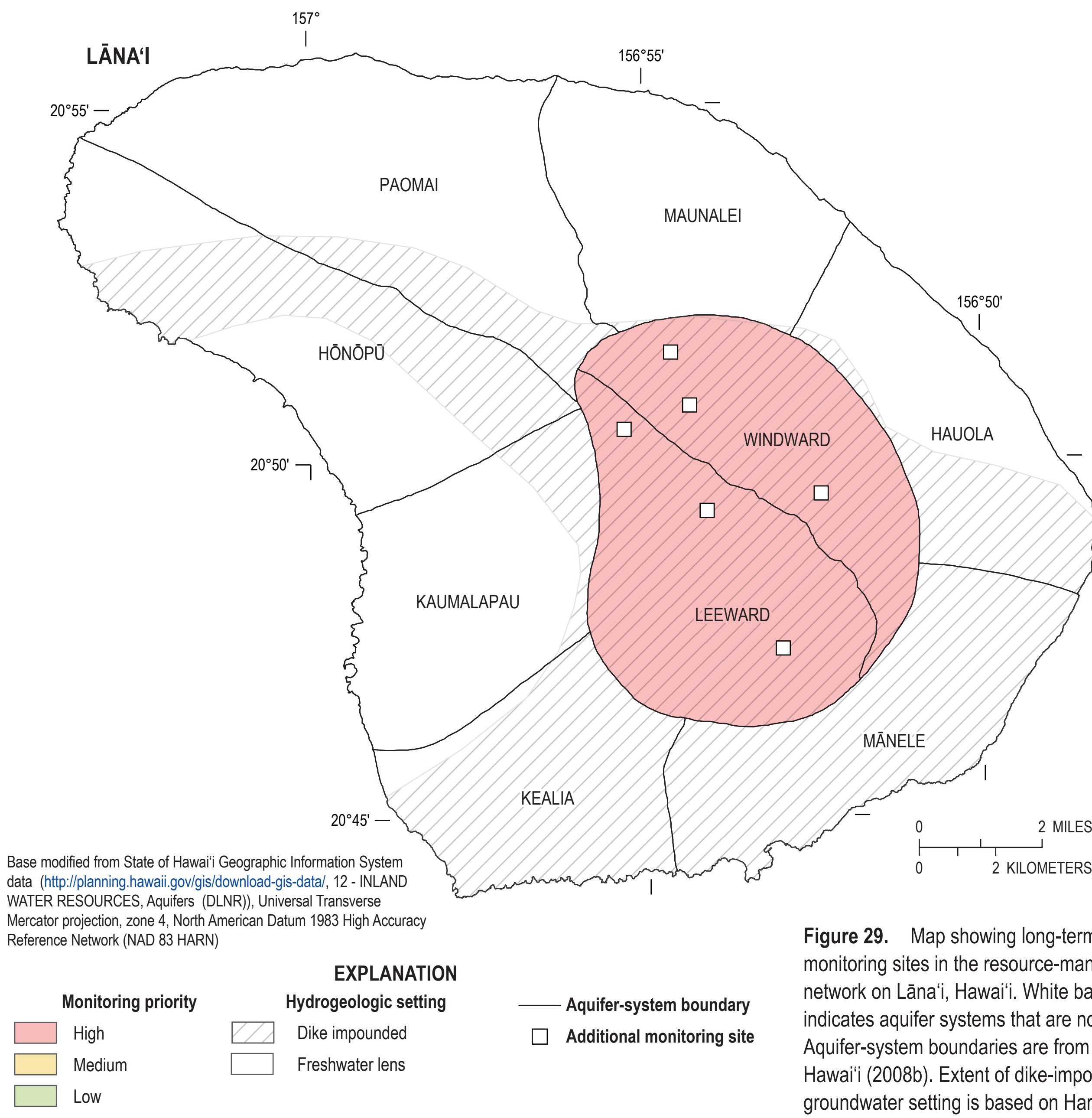



**Figure 29.** Map showing long-term water-level monitoring sites in the resource-management network on Lāna‘i, Hawai‘i. White background indicates aquifer systems that are not prioritized. Aquifer-system boundaries are from State of Hawai‘i (2008b). Extent of dike-impounded-groundwater setting is based on Hardy (1996).

effects on flows to surface or adjacent aquifer systems (Waihe‘e, ‘Īao, Pā‘ia, Ha‘ikū, and Makawao), concerns about recharge reduction caused by climate and (or) land-use changes (Launiupoko, Waihe‘e, ‘Īao, Kahului, Pā‘ia, Makawao, Honokōwai, and Kama‘ole), the aquifer system is a critical resource with no alternatives (Waihe‘e, ‘Īao, Kahului, and Kama‘ole), and hydrogeologic uncertainties (Ha‘ikū). In addition, the MDWS is concerned about the effects of an anticipated shift from surface-water to groundwater use in the Launiupoko aquifer system (MDWS, oral communication 2018).

Two aquifer systems in west Maui were identified as having a medium priority for groundwater monitoring. Criteria that contributed to the medium priority were concerns about declining storage (Honolua), concerns about effects on flows to the surface or adjacent aquifer systems (Waikapū), concerns about recharge reduction (Waikapū), and the aquifer system being a critical resource (Waikapū).

The Olowalu and Ke‘anae aquifer systems’ priority for groundwater monitoring were assessed as low. Although the entire Olowalu aquifer system lies in a region with a projected decrease in rainfall (fig. 17), little water is withdrawn from the aquifer system. Withdrawals from the Ke‘anae aquifer system could affect streams (Gingerich, 1999; and Meyer, 2000), but withdrawals are low, and the area receives some of the highest rainfall in the State (fig. 2). Twelve of the aquifer systems on Maui were not prioritized because they have little or no groundwater development, or the criteria used to identify monitoring needs did not pertain to them.

## Long-Term Water-Level Monitoring

Twelve long-term water-level sites are currently being monitored on Maui (fig. 30, table 17). Seven of the active sites are in the high-priority Waihe‘e and ‘Īao aquifer systems,

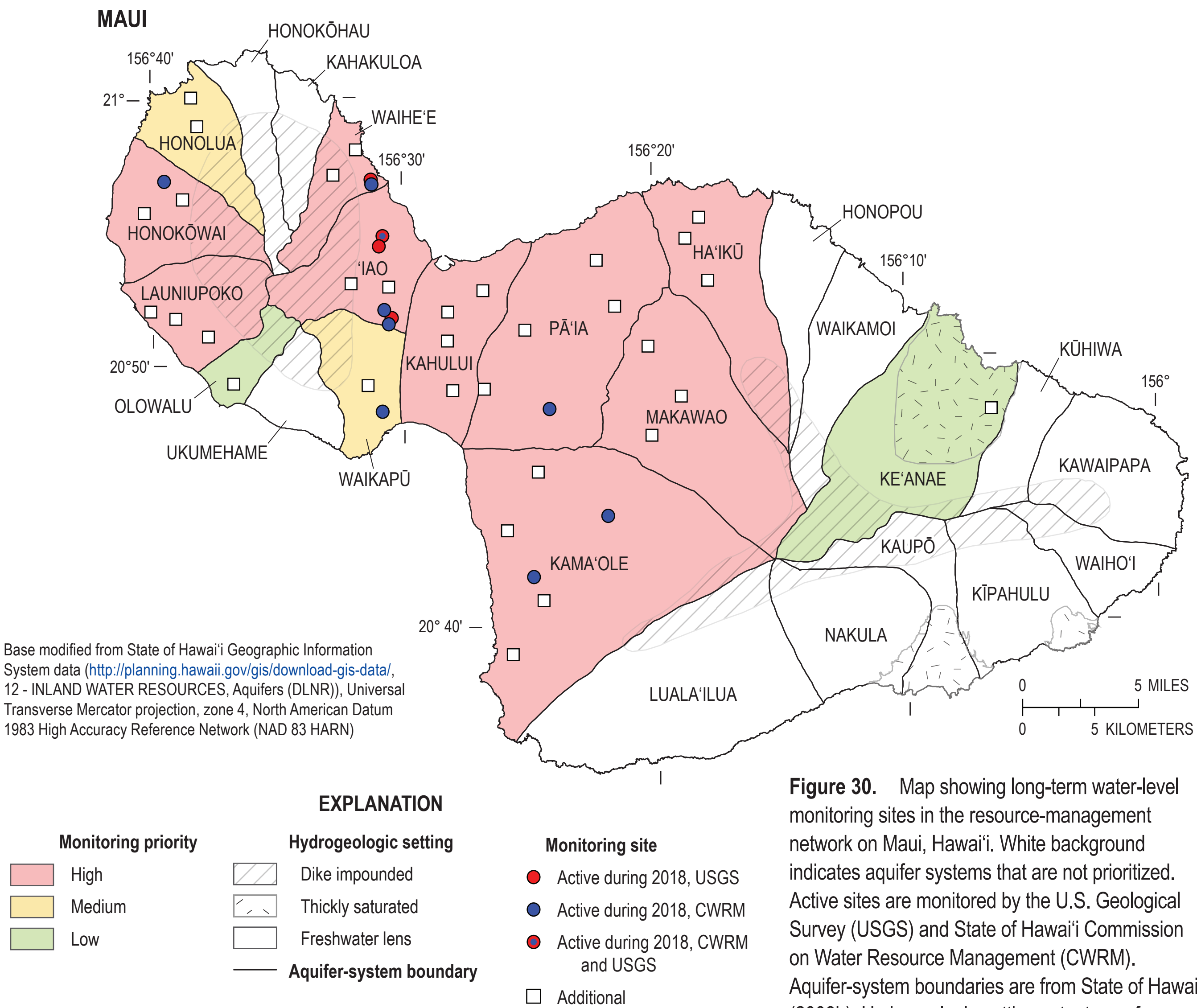



**Figure 30.** Map showing long-term water-level monitoring sites in the resource-management network on Maui, Hawai‘i. White background indicates aquifer systems that are not prioritized. Active sites are monitored by the U.S. Geological Survey (USGS) and State of Hawai‘i Commission on Water Resource Management (CWRM). Aquifer-system boundaries are from State of Hawai‘i (2008b). Hydrogeologic-setting extents are from Izuka and others (2018).

where water levels have declined since the first test well was drilled in the 1940s (State of Hawaiʻi, 2019c). The other four active sites are distributed in the high-priority Honokōwai, Pāʻia, and Kamaʻole aquifer systems. Four high-priority aquifer systems have no active long-term water-level sites. One medium-priority and two low-priority aquifer systems also are not currently monitored for long-term water levels.

The resource-management network for Maui includes 32 additional long-term water-level monitoring sites to supplement the current program (fig. 30). High-priority aquifer systems each have at least three active or additional sites, and as a group, the sites monitor water levels from inland to coastal areas, which is consistent with the regional water-level gradients on Maui. Some aquifer systems warrant more than three sites because of their large size (Pāʻia and Kamaʻole) or high withdrawal rates (ʻĪao and Kahului). Each of the two medium-priority aquifer systems on Maui have two long-term water-level monitoring sites, and each of the low-priority aquifer systems have one site.

## Specific-Conductance Profiling

Specific conductance is currently profiled at four sites on Maui (fig. 31, table 17). All of the active sites are in the freshwater-lens settings of the Waiheʻe, ʻĪao, and Honokōwai aquifer systems on west Maui. The active site in the northern part of the ʻĪao aquifer system has shown a rise in the transition zone over time (Gingerich, 2008; State of Hawaiʻi, 2019c), indicating a thinning of the freshwater lens. Large areas encompassed by the high- and medium-priority aquifer systems on Maui have no sites currently profiled for specific conductance.

The resource-management network includes 10 additional specific-conductance profiling sites for Maui. The network places

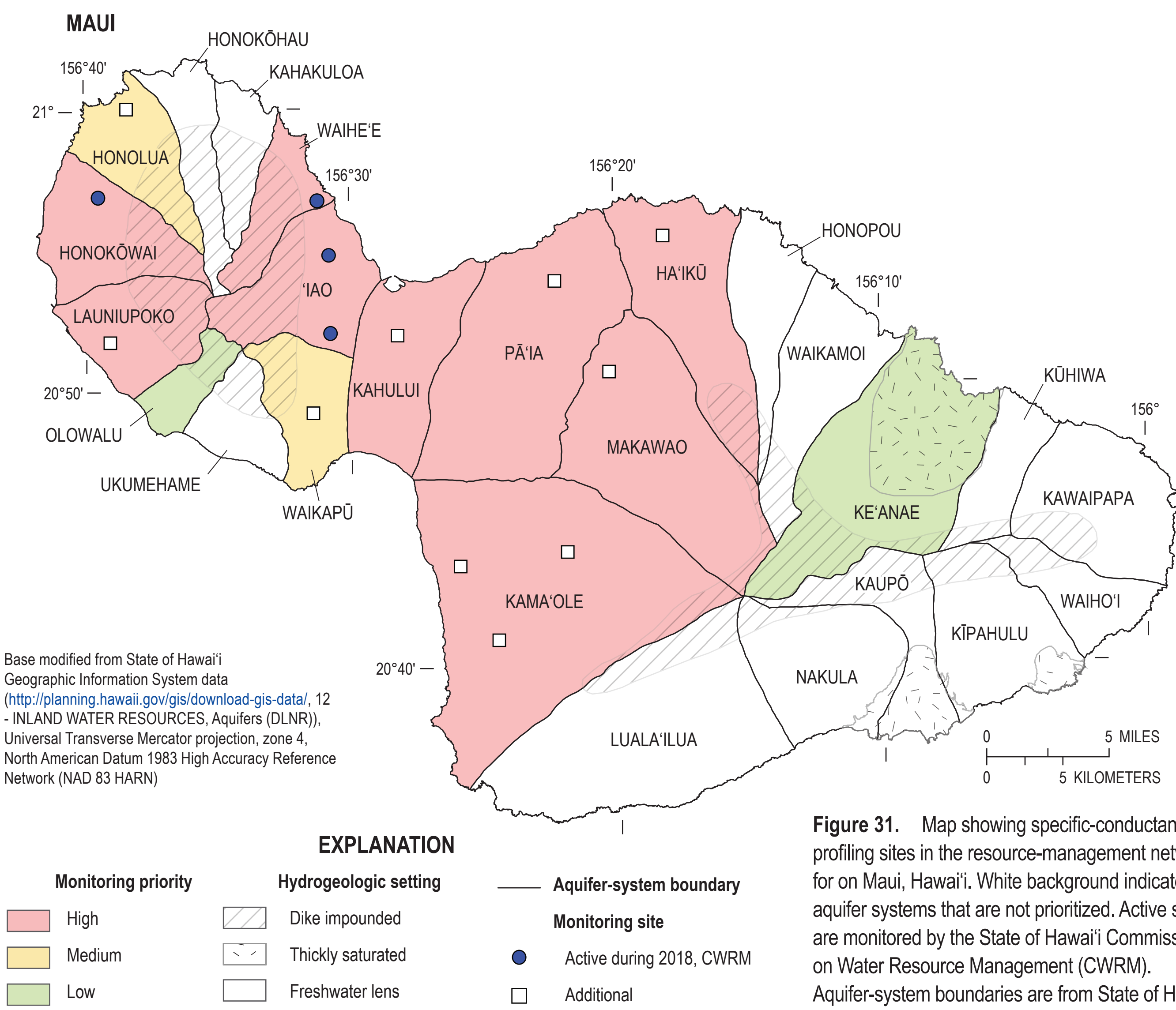
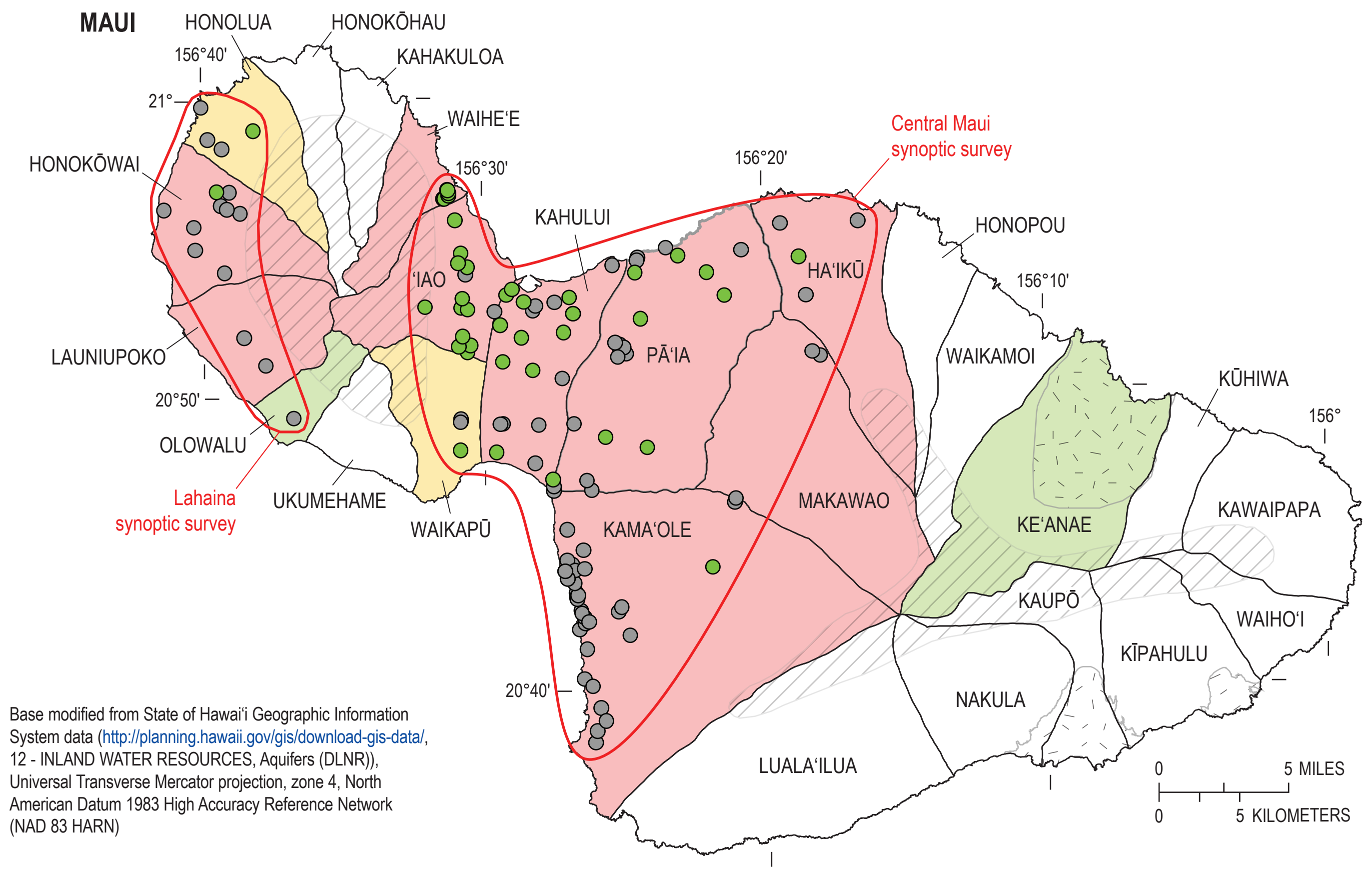



**Figure 31.** Map showing specific-conductance profiling sites in the resource-management network for on Maui, Hawaiʻi. White background indicates aquifer systems that are not prioritized. Active sites are monitored by the State of Hawaiʻi Commission on Water Resource Management (CWRM). Aquifer-system boundaries are from State of Hawaiʻi (2008b). Hydrogeologic-setting extents are from Izuka and others (2018).

at least one site in each of the high-priority aquifer systems. Six of these additional sites are distributed to achieve inland-to-coastal coverage for the high-priority aquifer systems on the western flank of Haleakalā. On west Maui, one site is selected for each of the high- or medium-priority Launiupoko, Honolua, and Waikapū aquifer systems. The ideal inland-to-coast arrangement of specific-conductance profiling sites is difficult to achieve on west Maui because the freshwater-lens setting is limited by the large area of dike intrusion in the interior of that part of the island. An additional site is selected in the Kahului aquifer system to monitor potential effects from land-use changes (especially changes in agricultural irrigation) on the isthmus.

## Synoptic Water-Level Surveys

Two synoptic water-level surveys are needed on Maui (fig. 32). The Lahaina synoptic survey is intended to monitor changes in the freshwater-lens settings in the high-priority Launiupoko and Honokōwai aquifer systems and the adjacent Honolua and Olowalu aquifer systems. The central Maui synoptic survey includes an area that was surveyed previously (USGS, 2013b), but it extends to the east and south to include additional wells where low-altitude water levels are similar to, and likely continuous with, those to the west. Because the survey includes wells scattered over a large area, however, measuring them all in the short period of a synoptic survey may be problematic. The survey may be feasible by selecting fewer wells for measurement while maintaining adequate data density and areal coverage, or by deploying recorders at some sites in advance. A less-ideal option is to divide the central Maui synoptic survey into east and west subsurveys that could be measured at different times; but a few wells should be part of both subsurveys to facilitate comparisons.




**EXPLANATION**

**Monitoring priority**
- High
- Medium
- Low

**Hydrogeologic setting**
- Dike impounded
- Thickly saturated
- Freshwater lens

**Line encompassing wells of one synoptic survey; label indicates name used in this report**

**Aquifer-system boundary**

**Known usable site**

**Potentially usable site**

**Figure 32.** Map showing synoptic water-level surveys on Maui, Hawai'i. White background indicates aquifer systems that are not prioritized. Aquifer-system boundaries are from State of Hawai'i (2008b). Hydrogeologic-setting extents are from Izuka and others (2018).

## Hawai‘i Island

Hawai‘i island has 24 aquifer systems, most of which are not prioritized because they have little or no groundwater development, or because criteria used to identify monitoring needs did not pertain to them (fig. 33). Four aquifer systems, all on the west side of the island, were identified as high priority because multiple criteria pertained to them, including high withdrawal (Waimea), concerns about declining storage and coastal discharge (Keauhou), concerns about effects on flows to adjacent aquifer systems (Waimea and ‘Anaeho‘omalu), and concerns about reductions in recharge caused by climate change (Waimea, ‘Anaeho‘omalu, Kīholo, and Keauhou). Many of the aquifer systems on the west side of Hawai‘i island also have hydrogeologic uncertainties—questions have been raised about the possibility of groundwater flow across the boundaries of the Waimea, ‘Anaeho‘omalu, and Kīholo aquifer systems (HDWS, oral commun., 2018), and the Keauhou aquifer system has an enigmatic high-level groundwater body, known as the Kona high-level groundwater, for which no definitive hydrogeologic cause has yet been identified (Oki, 1999; Bauer, 2003).

The Māhukona and Kealakekua aquifer systems on the west side of Hawai‘i island were identified as medium priority

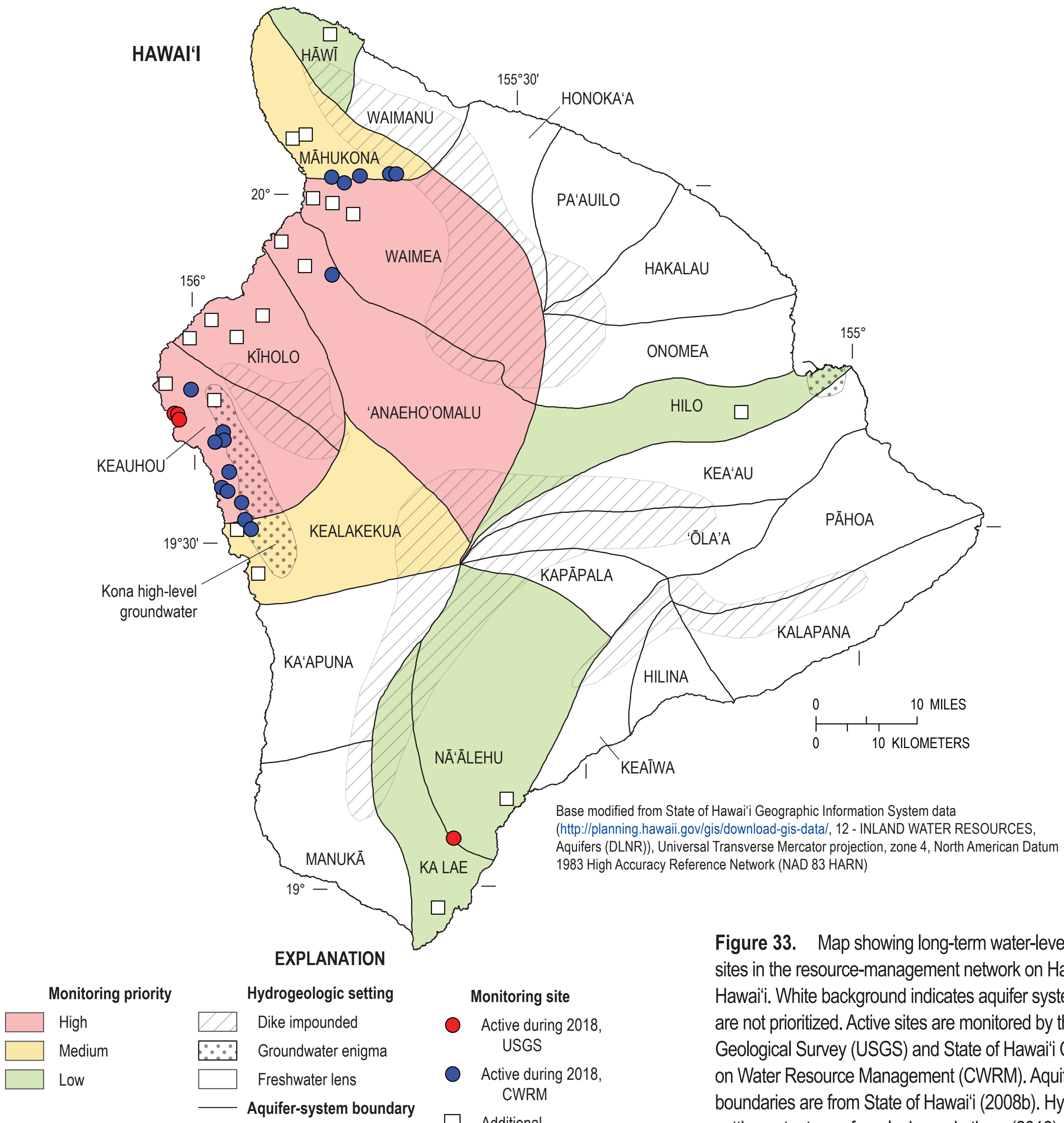



**Figure 33.** Map showing long-term water-level monitoring sites in the resource-management network on Hawai‘i island, Hawai‘i. White background indicates aquifer systems that are not prioritized. Active sites are monitored by the U.S. Geological Survey (USGS) and State of Hawai‘i Commission on Water Resource Management (CWRM). Aquifer-system boundaries are from State of Hawai‘i (2008b). Hydrogeologic-setting extents are from Izuka and others (2018).

for groundwater monitoring (fig. 33). Concerns related to these aquifer systems include recharge reduction, particularly resulting from climate change. Additionally, concerns related to the Kealakekua aquifer system include declining storage, and part of the enigmatic Kona high-level groundwater extends into northern part of the Kealakekua aquifer system. Uncertainties exist about the possibility of groundwater flow between the Māhukona and Waimea aquifer systems (HDWS, oral commun., 2018).

Four aquifer systems were identified as low priority for groundwater monitoring (fig. 33). The Ka Lae and Nāʻālehu aquifer systems have hydrogeologic uncertainties and both include regions in which projections indicate a possible decrease in rainfall (fig. 17), but little water is withdrawn from these aquifer systems. The Hilo aquifer system is critical to one of the island's major population and industrial centers, but it is in a high-rainfall area. The Hāwī aquifer system was a concern in the past when plans were considered to increase withdrawals; although these plans were not effectuated, CWRM considers monitoring of the aquifer system to be warranted for the future (CWRM, written commun., 2019).

### Long-Term Water-Level Monitoring

Hawaiʻi island has 21 active long-term water-level sites (fig. 33, table 17). Eleven of these active sites are in the vicinity of the Kona high-level groundwater in the Keauhou and Kealakekua aquifer systems, where declining water levels have been observed (State of Hawaiʻi, 2019c). A cluster of three wells monitored by the USGS provides data for assessing groundwater flow near the coast of the Keauhou aquifer system. Five sites are near the boundary between the Waimea and Māhukona aquifer systems, one is in the ʻAnaehoʻomalu aquifer system, and one is in the Nāʻālehu aquifer system near its southwestern border. The high-priority Kīholo and low-priority Hāwī, Hilo, and Ka Lae aquifer systems have no active sites.

Hawaiʻi island has 19 additional long-term water-level sites to achieve consistency with monitoring priorities (fig. 33). Four of the additional sites are in the vicinity of the Kona high-level groundwater, which is consistent with recommendations in the draft 2019 WRPP (State of Hawaiʻi, 2019c). The two medium-priority aquifer systems on Hawaiʻi island have active sites, but additional sites are needed to expand coverage to other parts of the aquifer systems. Each of the low-priority aquifer systems has at least one long-term water-level site.

### Specific-Conductance Profiling

Specific conductance is currently profiled at two sites on Hawaiʻi island (fig. 34). Both sites are in the freshwater-lens settings of the high-priority Keauhou aquifer system, seaward of the Kona high-level groundwater (table 17). Data from the southernmost of these two sites (Kahaluʻu DMW 8-3457-004) indicate a rising and expanding transition zone, which has been attributed to local groundwater withdrawal effects (State of Hawaiʻi, 2019c). None of the other high- or medium-priority aquifer systems on Hawaiʻi island have sites that are currently monitored for specific conductance.

This study places nine additional specific-conductance profiling sites on Hawaiʻi island. Two specific-conductance profile sites are in the high-priority Waimea, ʻAnaehoʻomalu, and Kīholo aquifer systems. These aquifer systems are large compared to those of other islands—all are larger than the entire island of Lānaʻi and can stretch tens of miles inland. Pairs of additional sites in these aquifer systems provide transects from inland to the coast but not all the way to the topographic divides that form the inland boundaries. An additional site is needed in the Keauhou aquifer system to provide additional data in the freshwater-lens setting along the Kona high-level groundwater. An additional specific-conductance profiling site is selected in each of the medium-priority aquifer systems on Hawaiʻi island.

### Synoptic Water-Level Surveys

Three synoptic water-level surveys are needed on Hawaiʻi island (fig. 35). The objective of the northwest Hawaiʻi synoptic survey is primarily to monitor water-table variations in the freshwater-lens settings of the high-priority Waimea, ʻAnaehoʻomalu, and Kīholo aquifer systems, although the survey includes collection of data from some inland wells that are known to have high water levels, probably as a result of dike intrusion. The Keauhou synoptic survey is intended to monitor changes in the water table in the vicinity of the enigmatic Kona high-level groundwater, which spans the Keauhou and part of the Kealakekua aquifer systems. The Māhukona synoptic survey is intended to monitor the water table of the freshwater-lens setting in the medium-priority Māhukona aquifer system.

## Climate-Response Network

Monitoring groundwater resources for climate response is evaluated on a statewide basis rather than the island-by-island basis that was used for resource-management network. The climate-response network was evaluated for how well active sites cover the range of hydrogeologic settings (freshwater-lens, dike-impounded-groundwater, and thickly saturated settings) and climate settings in Hawaiʻi. For climate settings in this evaluation, the land area of each island was divided into three categories representing percentage difference between projected future (2041–2071, RCP 8.5) and present (1978–2007) average rainfall (Elison Timm and others, 2015; fig. 36):

- *Drier.*—Projections indicate future rainfall will be lower by 15 percent or more.
- *Same.*—These are areas where future rainfall is projected to be between 0 and 15 percent lower than present.
- *Wetter.*—Projections indicate future rainfall will be greater than present.

The objective for the monitoring program is to create a climate-response network in which all combinations of climate

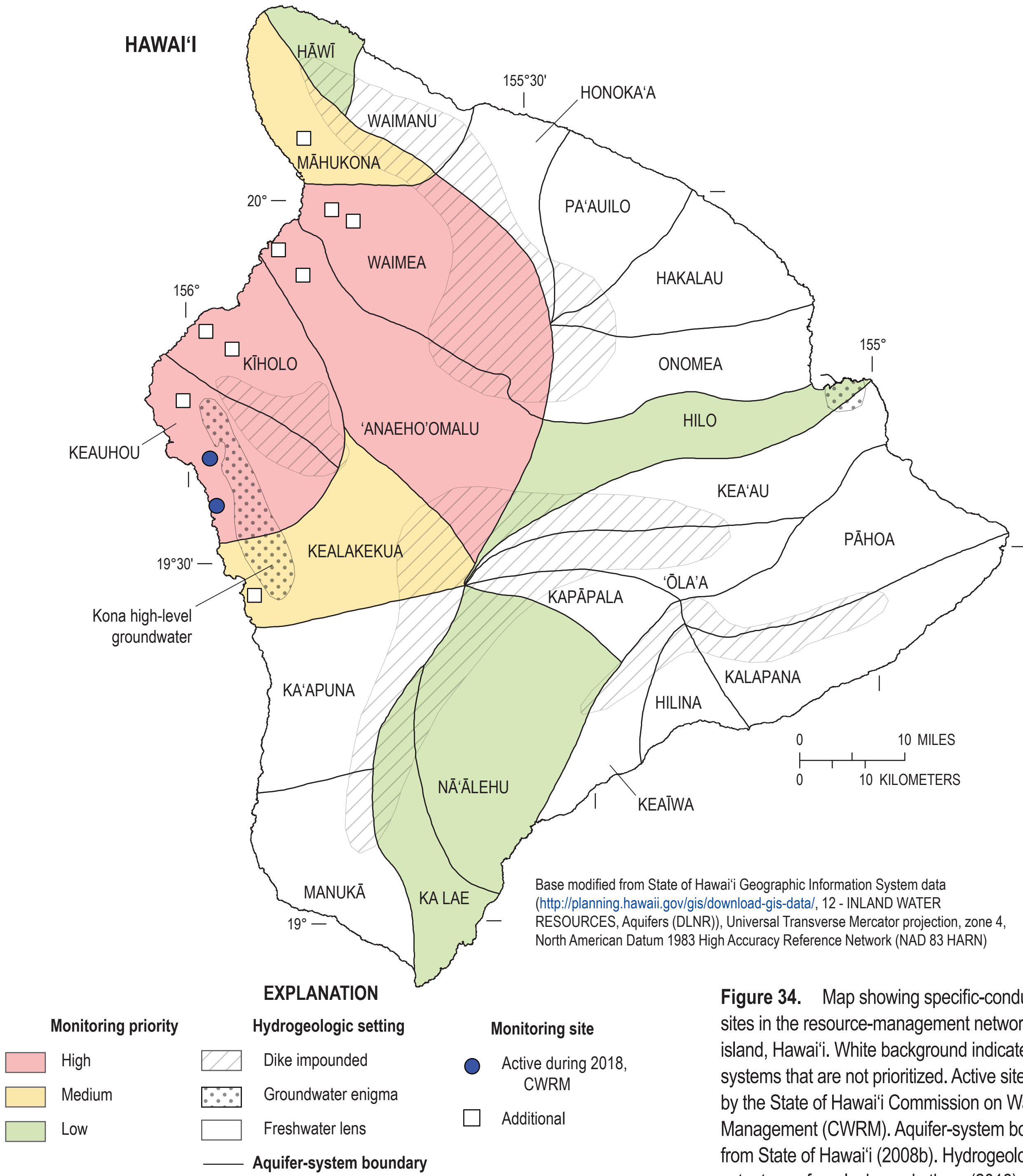



**Figure 34.** Map showing specific-conductance profiling sites in the resource-management network on Hawai‘i island, Hawai‘i. White background indicates aquifer systems that are not prioritized. Active sites are monitored by the State of Hawai‘i Commission on Water Resource Management (CWRM). Aquifer-system boundaries are from State of Hawai‘i (2008b). Hydrogeologic-setting extents are from Izuka and others (2018).

and hydrogeologic settings are monitored. Site selection is constrained to areas where anthropogenic effects, such as those from pumped wells or land-use changes, do not obscure the effects of climate on the aquifer.

Two groundwater-monitoring strategies are considered for the climate-response network: long-term water-level monitoring and specific-conductance profiling. As discussed earlier in this report, long-term water-level monitoring is warranted in all hydrologic settings, whereas specific-conductance profiling is primarily useful in the freshwater-lens setting. Specific-conductance profiling sites generally are more costly to establish and operate than water-level monitoring sites because specific-conductance profiling usually requires construction of a DMW specifically for the purpose and data are more complicated to acquire and process. The practical limits owing to the relative costs of these methods are also considered—specific-conductance profiles are selected for only a few representative climate and hydrogeologic settings.

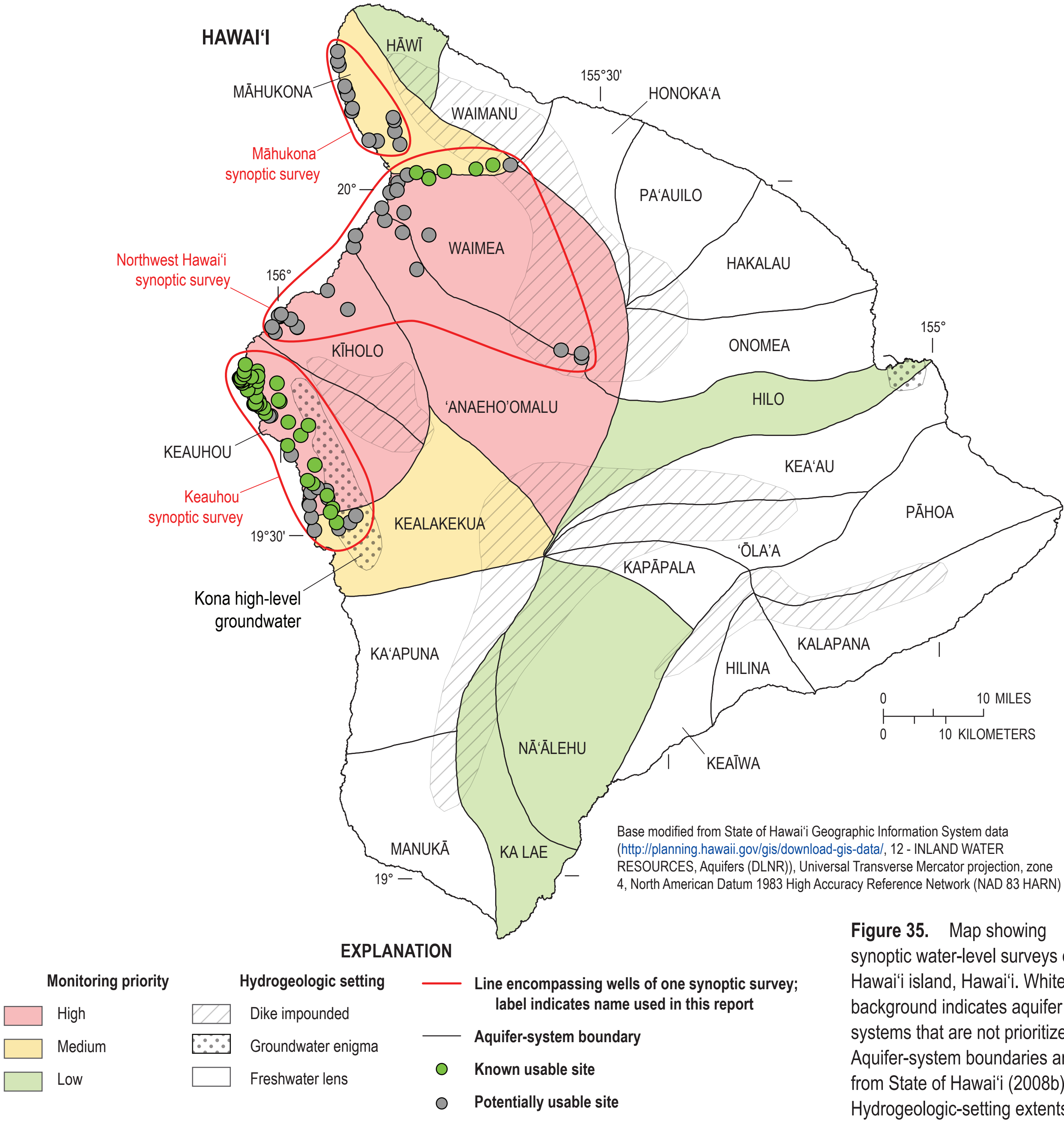



**Figure 35.** Map showing synoptic water-level surveys on Hawaiʻi island, Hawaiʻi. White background indicates aquifer systems that are not prioritized. Aquifer-system boundaries are from State of Hawaiʻi (2008b). Hydrogeologic-setting extents are from Izuka and others (2018).

## Active Monitoring Sites

The climate-response network has three active wells, one each on Kauaʻi, Molokaʻi, and Hawaiʻi island. All three sites monitor long-term water levels (fig. 36, table 18); no specific-conductance profiling is currently done specifically to evaluate climate response in Hawaiʻi.

Active well 2-0126-001 (NW Kilohana Mon) is in a thickly saturated setting and an area where future rainfall is projected to remain about the same on Kauaʻi (fig. 36, table 18). The site is in a high-priority aquifer system (Wailua); however, the high-priority ranking comes from criteria other than withdrawals, and the site is far from currently pumped wells. Although future groundwater development could increase withdrawals, the areal extent of water-table depression by pumped wells in this low-permeability setting is limited by streams (Izuka and Oki, 2002). Because this well is the only active site in the thickly saturated setting and has more than 20 years of data, its continuation in the climate-response network is needed.

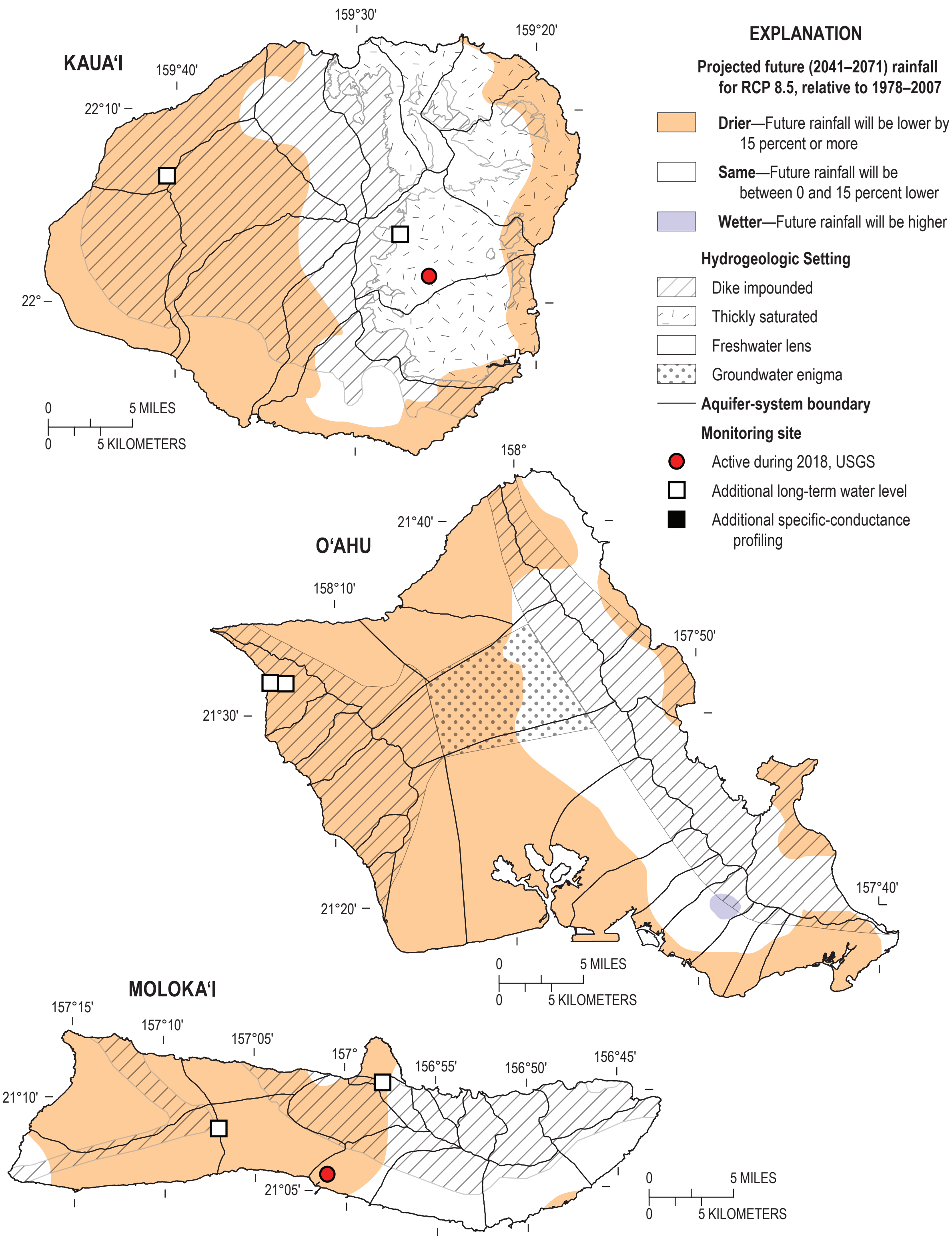



**Figure 36.** Maps showing the climate-response network for the groundwater-resource monitoring program for the Hawaiian Islands of Kaua‘i, O‘ahu, Moloka‘i, Maui, Lāna‘i, and Hawai‘i, including long-term water-level and specific-conductance-profiling sites. Active sites are monitored by the U.S. Geological Survey (USGS). Rainfall projections are from statistical downscaling by Elison Timm and others (2015) for representative concentration pathway (RCP) 8.5 from the Intergovernmental Panel on Climate Change. Aquifer-system boundaries are from State of Hawai‘i (2008b). Hydrogeologic-setting extents are from Izuka and others (2018).

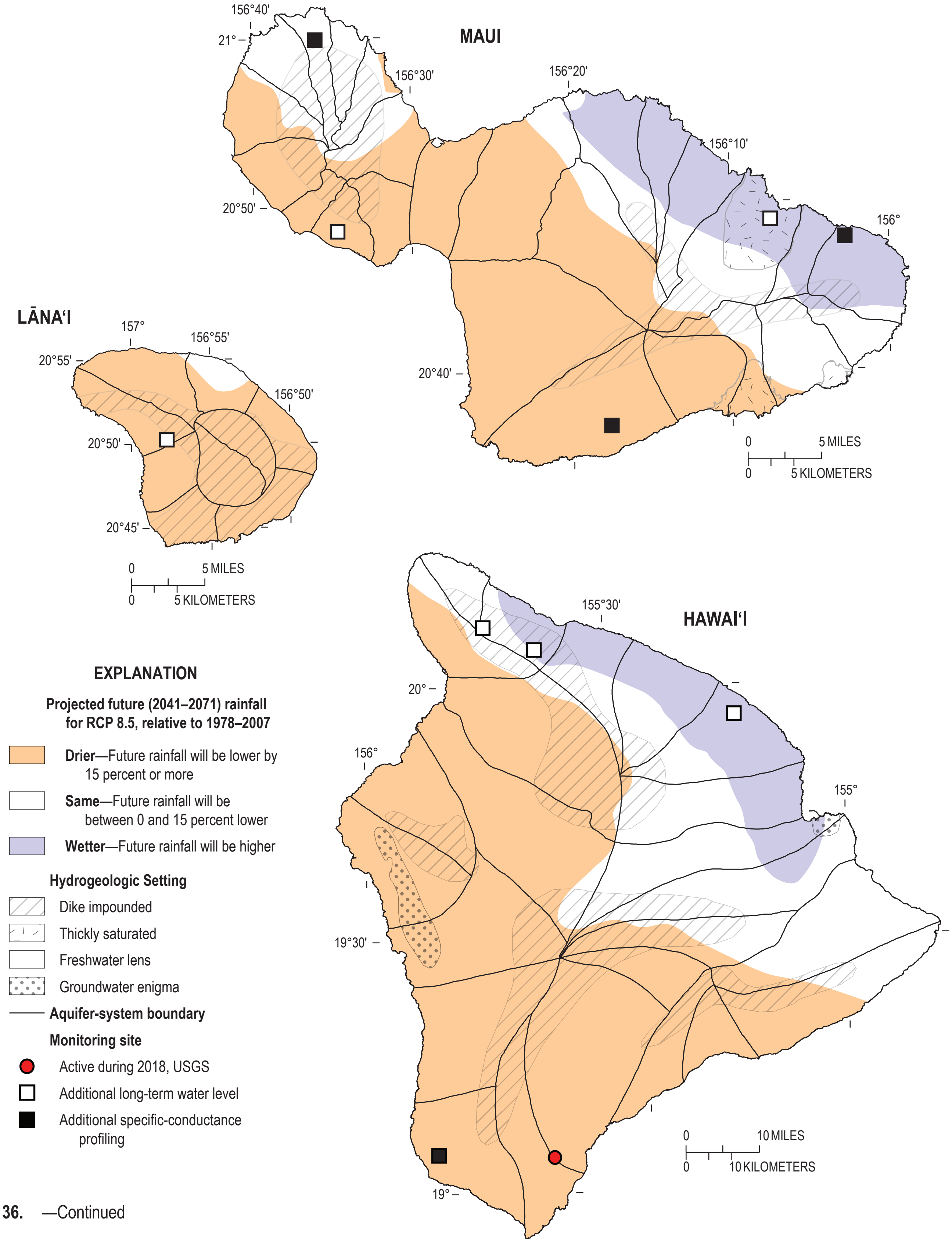



**Figure 36.** —Continued

**Table 18.** Active groundwater sites currently (2018) monitored for response to climate variations in Hawai‘i.

[Projected climate change is based on Elison Timm and others (2015) for representative concentration pathway (RCP) 8.5, 2041–2071. Latitude and longitude in decimal degrees for North American Datum of 1983. Names are from the State of Hawai‘i Commission on Water Resource Management's (CWRM) well database, except where indicated. First-year-of-data column: dates are for data in National Water Information System (NWIS), although earlier data may exist that is not in NWIS]

| State number | Name | Type | Projected climate change | Hydrogeologic setting | Location | | | Agency | First year of data |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | Island | Latitude | Longitude | | |
| 2-0126-001 | NW Kilohana Mon | LTW | Same | Thickly saturated | Kaua‘i | 22.0233 | −159.4323 | USGS | 1996 |
| None | Kaunakakai | LTW | Drier | Freshwater lens | Moloka‘i | 21.0970 | −157.0174 | USGS | 1954 |
| 8-0437-001 | Waiohinu Exploratory | LTW | Drier | Uncertain | Hawai‘i | 19.0697 | −155.6184 | USGS | 1997 |

An actively monitored well with the name "Kaunakakai" (but with no state number) is in the medium-priority Kamiloloa aquifer system on Moloka‘i (fig. 36; tables 17, 18). The site is in a freshwater-lens setting and an area where future rainfall is projected to decrease. Continuation of the site as part of the climate-response network is needed because the site has more than 60 years of data, although potential future increases in withdrawals from the Kamiloloa and adjacent aquifer systems could affect the site and obscure climate response.

Active well 8-0437-001 (Waiohinu Exploratory) on Hawai‘i island is in an area of uncertain hydrogeology. Water levels are hundreds of feet above sea level, which is not consistent with a freshwater-lens setting, but they are also not associated with a known rift zone where dike-impounded groundwater may exist. The high water levels in this well cannot be perched—the well penetrates below sea level, yet water levels remain more than 1,000 ft above sea level. The well lies in an area where geologic maps (Sherrod and others, 2007) show a complex of faults, but it is not known if the high-water levels are related to the faults. Despite the hydrogeologic uncertainty, the site is included in the climate-response network because it has more than 20 years of data, is in a remote area where climate response is unlikely to be obscured by anthropogenic activity and is in an area where future rainfall is projected to decrease.

### Additional Monitoring Sites

The climate-response network includes 16 additional sites to supplement the 3 active sites in the current program (fig. 36). Additional sites are included primarily in aquifer systems that are not prioritized for water-resource management—because these aquifer systems have little or no groundwater development, they are ideal for isolating climate effects. One site (on Kaua‘i) is also part of the additional sites in the long-term water level network.

The active and additional water-level monitoring sites in the network span most of the climate settings and three of the four hydrogeologic settings considered (fig. 36, table 18). Most additional sites are in areas that are projected to become drier in the future; concerns for water-resource availability will be more critical if projected rainfall decreases become reality. Most sites are also in freshwater-lens settings; freshwater lenses provide most of the water resources used by humans in Hawai‘i. Sites in the freshwater-lens settings represent all three climate settings. No sites in the network monitor water levels in a thickly saturated setting where climate is projected to become drier. Except for a small remote area in southern Maui, thickly saturated settings are in areas where climate is projected to become wetter or stay about the same.

Two of the additional sites are within a few miles of active sites and in similar climate and (or) hydrogeologic settings. The additional sites are selected to supplement the active sites and potentially replace them if the active sites become affected by development that will obscure climate effects. One of these additional sites is about 3 miles to the northwest of well 2-0126-001 on Kaua‘i, farther from potential development (fig. 36). Another additional site is about 7 miles to the west-northwest of the active Kaunakakai well, in an area that is less likely to be developed for groundwater. Ideally, these additional sites would be monitored concurrently with the active sites before development affects them.

Specific-conductance profiling is needed at four additional sites in freshwater-lens settings (fig. 36, table 18). Two of the sites are in areas that are projected to become drier, one in an area that is projected to remain about the same, and one in an area that is projected to become wetter.

## Data-Quality Objectives

Under the paradigm of integrated water-resource management and protection, decision makers are increasingly having to recognize potentially competing social, economic, and cultural values of water resources. Informed decision making for equitable and sustainable water management is highly dependent on accurate and reliable hydrologic data, commonly from multiple sources. Appropriate and consistent data quality and accessibility are necessary to ensure usability of the data. Hudson and others (1999) emphasized the importance and need for hydrologic data-collection programs to focus on capturing data that are fit for their intended purpose. In times of reduced funding for hydrologic monitoring, clear and effective communication between managers and users of data will increase the likelihood that collected data are useful, that current and future data needs are identified, and that the data will meet quality standards for those needs.

The data-quality objectives (DQO) process identifies performance criteria for collecting data of sufficient quality and quantity needed to support program goals. In water-resource management, DQO are often used to determine the degree of uncertainty tolerable in a dataset to achieve confidence in management decisions that are based on the data (U.S. Environmental Protection Agency [EPA], 2006). Data that are adequate for one purpose may be inadequate for another (Keith and others, 1983); the quality of data needed is dependent on the current water-resource issues and local regulatory restrictions that may change over time (Granato and others, 1998).

Rainfall, surface-water, and groundwater data have been collected by government agencies and private entities in Hawai‘i for over a century. These data are a potential source of historical information that can be valuable for current and future resource assessments and scientific research. The data were collected for various purposes, and with various methods and levels of precision. In some cases, metadata describing the methods and precision have not been preserved, or no record exists of quality assurance and quality control (QA/QC) measures, which leads to data-quality uncertainties that may limit the utility of the data. No common data-quality plan exists for all data-collection agencies in Hawai‘i, and each agency follows its own protocol. Establishment of common DQO not only assures comparability of data collected by multiple agencies, but it also allows data from academic, private, and public organizations to be useful for meeting State monitoring needs if their data meet appropriate DQO and can be made available to the public.

The DQO process in water-resource management is commonly an iterative process that involves identifying (1) current water-resource issues, (2) monitoring design and goals, (3) acceptable accuracy and uncertainty in the data collected, (4) QA/QC, and (5) data-accessibility requirements. Other sections of this report address the first two components of the DQO process by summarizing current water-resource issues and describing design and goals of the rainfall, surface-water and groundwater monitoring programs. The remaining three components of the DQO process are described in the following sections. DQO specific to rainfall, surface water, and groundwater are described separately.

## Acceptable Accuracy and Uncertainty

The accuracy of a measurement relates to how well the measured value compares with the true value. It is a function of the resolution at which the data are being collected and of any systematic and random errors in a measurement. Resolution refers to the smallest increment in measuring unit and time an instrument can discern. Systematic-measurement errors are biases introduced into the measurement, which can be reduced or eliminated if the cause of such errors is identified and quantified. Random errors are unpredictable fluctuations in the measurement data that can be reduced by increasing the number of observations or samples. In many cases, data collected at fine resolution with minimal measurement errors have a wider range of uses than those collected at coarse resolution with large errors.

Uncertainties in hydrologic data propagate to uncertainties in hydrologic analyses and interpretations, and consequently to resource-management decisions and policies (McMillan and others, 2018; Wilby and others, 2017). Accounting for hydrologic-data uncertainty is crucial to developing scientifically defensible and cost-effective water-resource management decisions (McMillian and others, 2017). Furthermore, transparent declaration and understanding of the data limitations promote trust between hydrologic-data managers, decisions makers, and the public. McMillan and others (2018) summarized the causes of uncertainty into five categories: uncertainty associated with measurement errors, derived or estimated data, interpolated data, scaling of data, and data-management errors. Collecting replicate and nested measurements, subsampling and resampling (bootstrapping), applying results of empirical or laboratory studies, and using statistical approaches to express probability of occurrence are all valid methods of quantifying data uncertainty (McMillan and others, 2018). Instruments may have software that estimate measurement uncertainty using these methods.

## Quality Assurance and Quality Control

Hydrologic data are valuable because they represent information with which resource-management strategies and decision-making tools are developed. To preserve that value, maintaining traceability of the data by documenting methods used to collect and process the data is crucial. Programs that maintain QA/QC are used to evaluate all aspects of a data-collection effort, including program design, data collection, data analysis, documentation, and reporting. Standard procedures and methods for data collection, data processing, data archiving, and expressing data accuracy and uncertainty are often reviewed for compliancy and consistency. Programs that maintain QA/QC preserve the integrity of the data by detecting and controlling errors and documenting uncertainties in the data (Granato and others, 1998).

Data validation is an important component of QA/QC programs. Data validation refers to identifying anomalies in the dataset and occurs during all aspects of data collection and data processing. Routine instrument calibration and station inspections by trained personnel are necessary components of data-validation procedures to ensure that the data collected are not affected by equipment errors. Field-validation procedures typically involve comparing the data with independent readings to detect errors in time and magnitude. For example, stage (water level) at a streamflow-gaging station is measured from a reference gage and compared with the water-level recorder reading to identify instrument drift (deviation in instrument performance). Automated-validation procedures commonly involve detecting and subsequently flagging values falling outside of established thresholds and expected ranges of variables. The person validating the data may use a combination of on-site independent readings, field-inspection notes, and results from instrument calibration tests to determine whether to accept, reject, or correct the values in question. Statistical and graphical methods are particularly useful in validating continuous data.

Programs that maintain QA/QC are essential to any data-collection effort to ensure that data are reliable and defensible (Childress and others, 1987). Data that are admissible as legal evidence must be relevant, material, and competent (Granato and others, 1998). Relevancy and materiality support the issue in question and are specific to the case. Competency refers to the quality and validity of the data; competent data used as legal evidence are technically defensible. Proper QA/QC practices enable the data to withstand court challenges to their quality, reliability, and veracity.

## Data-Accessibility Requirements

Data accessibility is critical to integrated water-resource planning, management, and protection. It allows for cost-efficient data-collection efforts by eliminating duplicate efforts for the same objective, or by cost sharing to develop higher utility datasets that meet multiple objectives. Data that are appropriately collected, managed, and made accessible are important for meeting the needs of the people using the data. A decision is made on whether a dataset should be open access—available to the public—or controlled access—restricted to specific users. Publicly available data promote transparency in water-resource regulation and enforcement; however, controlled access may be necessary for sensitive information that may be related to National security or proprietary information. Real-time data are required for resolving time-sensitive issues such as flood warning and meeting instream-flow standards. Easily accessible data can be provided through open-source platforms.

In Hawai‘i, rainfall, surface-water, and groundwater data collected by the USGS are publicly available on NWIS Web (https://waterdata.usgs.gov/nwis)—most rainfall, surface-water, and selected groundwater data are given in real-time. CWRM also collects streamflow data at selected locations to regulate instream-flow standards, and their data are available on their website (https://dlnr.hawaii.gov/cwrm/surfacewater/monitoring/) with some sites in real-time. Water-use data collected by CWRM and data collected by County agencies commonly are available upon written request.

## Metadata

Protocols for responsible data sharing and public access are necessary to support appropriate use and interpretation of the data. Metadata describe the data and are oftentimes needed to facilitate the use of the data. Utility of the data increases when metadata are made available with the dataset. Metadata standards allow determination of data comparability among different data-collection agencies, so data from multiple sources can be used collectively to address a common water-resource issue. Metadata standards for hydrologic monitoring may consist of, but are not limited to, the following:

- Description of data collected or parameter evaluated;
- collection frequency;
- standard procedures for data collection, processing, archiving, and dissemination;
- analytical methods of translating data into information;
- standards for data accuracy;
- methods for expressing data uncertainty;
- QA/QC program relevant to the data;
- location (geographic coordinates in latitude and longitude) of data collection;
- date and time of data collection;
- data-collection entity; and
- data quality (accuracy and uncertainty).

A statewide integrated water-data platform that combines existing water-resource and water-use information from multiple agencies and (or) databases will help create and refine decision-support tools in water-resource management.

## Space and Time Characterizations

General space and time parameters pertain to more than one type of monitoring. Geographic coordinates and time are parameters that are part of rainfall, surface-water, and groundwater monitoring discussed in this report. Relative altitude (vertical linear measurement made relative to an arbitrary datum) is sometimes part of surface-water monitoring, and absolute altitude (vertical linear measurement above mean sea-level datum) is part of groundwater monitoring.

Location of data collection can be expressed as a general geographic location of the data-collection effort or geographic coordinates (latitude and longitude) and altitude of a data point. Geographic coordinates of a rain-gage, streamflow-gaging station, and well location on the earth's surface are relative to a geodetic datum, but different datums have been used historically to map locations in Hawai‘i (for example, Old Hawaiian Datum, North American Datum of 1983 [NAD83], World Geodetic System of 1984 [WGS 84]). Coordinates from one geodetic datum are not directly comparable to those from another datum. Coordinates from one datum can be transformed to another datum if the original datum is known. Therefore, the datum should be stated with the geographic coordinates in the metadata documentation.

Accurate measurement and complete recording of time, whether by field personnel, field computers, or automated data loggers is essential. At a minimum, time records must include the date, time of day (commonly to the nearest minute), and whether the recorded time is in Hawai‘i-Aleutian Standard Time or Coordinated Universal Time. To facilitate comparison of datasets collected at different locations, over different periods, or by different methods, all measuring devices must be synchronized to a consistent time reference (for example, National Institute of Standards and Technology [NIST] time). This

synchronization must be done before each field visit, because different timing devices (clocks, wristwatches, and data loggers) have different instrument-drift rates. If a data logger has been left to record for a long period, discrepancies between its clock and the consistent reference should be noted, so corrections can be made in the time data if needed. The logger's clock can then be reset to the consistent time reference and redeployed.

## Rainfall

Accurate, spatially diverse rainfall data are required by a variety of end users; however, differences in DQO among the collecting agencies can affect the usefulness of the data. The goal of this section is to address those DQO that will facilitate the accurate and reliable collection and archiving of rainfall data, thus maximizing the utility of the data. The WMO (2008, 2014, and 2018) provides general guidelines and practices for the collection and processing of rainfall data, and they should be used as a reference for understanding and implementing a rainfall-monitoring program. Two approaches are used for rainfall data collection—manually read gages that are human dependent for data collection and automated rain gages that use sensors and data recorders to measure and store the information. Because of the inherent limitations of manually read rain gages, the rainfall-monitoring program is only considering the use of automated gages. Therefore, this section summarizes the WMO-recommended guidelines that can pertain to the accuracy and quality of time-series rainfall measurements for automated rain gages.

The automated time-series monitoring of rainfall provides a record of how much rain has fallen using an instrument that records the amount of water collected during a specified measurement interval and transmits that information to a data logger. Each instrument type has mechanical design drawbacks that can potentially limit the accuracy of the measurement. Environmental factors such as gage exposure to strong winds or gage placement in relation to other objects or geographic features can also affect the collection of accurate rainfall data. Other sources of error can come from the automated data-collection process and are result from data processing and archiving. These sources of potential error need to be systematically addressed using QA/QC procedures that will maximize the dataset's validity and usability.

### Proper Installation and Maintenance

The proper installation of a rain gage is critical to the collection of accurate rainfall data. The capability of a rain gage to collect a representative amount of rainfall is directly related to the rain exposure it has. Wind can affect the collection of rainfall and alter the gage reading in two different ways. A rain gage that is not sheltered from strong wind can create turbulent air around the orifice, reducing the amount of rain collected by the gage. Large objects and geographic features in the immediate vicinity can alter wind direction in a manner that can either increase or decrease the amount of rain that makes it into the gage. An ideal rain gage placement is one that includes some protection from strong winds on all sides by objects taller than the top of the rain gage. However, the height of the surrounding objects above the gage orifice should be at least equal to half the horizontal distance from the object to the gage but not exceeding the total horizontal distance (see WMO, 2008, fig. I.3.1). Sites located near steep slopes or cliffs should be avoided because of their influence on wind direction and turbulence. A rain gage should be installed as low to the ground as possible. In exposed windy locations with no natural shelter, the gage can be installed in the ground in a manner that will remove splash induced accumulation (see WMO, 2008, fig. I.3.1).

Appropriate instrumentation for the environment of monitoring and routine maintenance will minimize the effects on the quality of data. A variety of rain gages can be used to directly measure the accumulation of rainfall over time. Each type of gage has its advantages and limitations that are associated with the mechanical design. A thorough discussion of each rain-gage type can be found in the Guide to Hydrological Practices (WMO, 2008, Chapter 3), which is useful for evaluating the type of gage that best suits its intended purpose and location. The routine maintenance of the equipment and the areas surrounding the gage is necessary. Vegetative growth in the vicinity of the gage must be cleared periodically, so it does not block the gage's rainfall exposure. The rain-gage orifice should be inspected for debris that can block the collection of rainfall and result in inaccurate data. All components associated with the data recorder and power supply need to be inspected and kept in good condition. Calibration of the rain gage should be done at least once a year or more frequently to avoid discarding long periods of data because of a faulty gage. Documentation of all routine maintenance inspections should be standardized.

### Recording Interval

The recording or measurement interval is the amount of time that passes during which the accumulation of rainfall is recorded as a data point. The interval at which rainfall accumulation is recorded and how quickly that data point is accessed directly affects how that data can be used. Real-time recording and transmission of data at intervals of 15 minutes or less can provide advanced flood warning during storms. Short measurement intervals also provide rainfall data used by watershed modelers for understanding rainfall-runoff processes, and they provide intensity and duration values used by engineers when designing infrastructure systems. In contrast, daily totals are used for long-term observations used to calculate monthly, yearly, or base-period averages, which provide necessary information for a variety of end users. The measurement interval and method of dissemination must, therefore, be determined depending on the purpose of each rain gage and is therefore site dependent. If the recording resolution is on the order of minutes, the time stamp of the data points should be standardized so that when summed, they will start and (or) end on the hour. Hourly measurements need to be collected on the hour, and if the recording resolution is a daily 24-hour period, the measurement

interval should not span across more than one-calendar day. In general, standardization of data collection times is useful when comparing data from different stations. All of these details should be included in the metadata documentation.

### Data Validation

Because of the intermittent nature of rainfall, it is not always possible to know if a valid data point has been removed or flagged as erroneous (type I error), or if an invalid data point is included within a dataset (type II error). Data validation is important for identifying anomalous climate events producing data points that have been removed or flagged as outliers. The WMO (2008, chapter 9) provides general guidelines for data validation and quality control with more detailed approaches related to a variety of climatological data discussed by Durre and others (2008), Estevez and others (2011), Hubbard and others (2005), and Shafer and others (2000).

## Surface Water

Surface-water data in Hawaiʻi are used in many applications to generate information that is useful for various purposes in surface-water resource management. Three major purposes for surface-water data in resource management include regulation of instream-flow standards, characterization of regional hydrology, and evaluation of long-term trends in streamflow. Each of these uses require data of high quality, accuracy, and accessibility to ensure development of proper and effective surface-water management decisions.

Conflicts between users of surface-water resources oftentimes result in litigation over rights to the water. The presiding official may question the validity, integrity, and accuracy of the streamflow data that were used to determine the flow standards. Metadata should be preserved to allow the public to assess the quality and usefulness of the data.

Real-time streamflow data are critical for monitoring instream-flow standards. Flow standards are typically established downstream from surface-water diversions to ensure continuous flow to the ocean for supporting native aquatic life and to ensure that sufficient streamflow is available to downstream users. Real-time monitoring allows for transparent enforcement of flow standards and equitable allocation of surface water at all times.

WMO (2008, 2010a, and 2010b) discusses common practices for producing accurate continuous record of discharge, and these references are useful for understanding the theory and rationale supporting each practice. Rantz and others (1982), Sauer (2002), Sauer and Turnipseed (2010), and Turnipseed and Sauer (2010) discuss practices employed by the USGS and these practices are summarized in the following subsections.

A continuous-record streamflow-gaging station provides a continuous record of discharge by using instruments that sense and record water-surface elevation in the stream (stage) that is then converted to discharge by applying a stage-discharge relation (rating), which is developed with measurements of discharge and corresponding measurements of stage made at the station. Reliable and accurate continuous streamflow data require (1) proper location, installation, and maintenance of a streamflow-gaging station, (2) accurate measurement of stage, (3) routine differential leveling, and (4) satisfactory direct-discharge measurement.

### Proper Location, Installation, and Maintenance

Effective site selection, correct design and construction, and regular maintenance of a gaging station are necessary for producing complete records of accurate streamflow data and reducing the need to estimate any missing records, which could introduce significant sources of errors in the streamflow record. Site selection for a continuous-record station involves locating stable controls that promote a stage-discharge relation that does not change over time and that has a proximate and flow-representative stream reach for making direct measurements of discharge throughout the range of stage. A hydraulic control is a reach of the stream channel, located downstream from the gage, that is capable of stabilizing the flow past the gage and eliminating the effect of all channel features downstream from the control on the velocity of the flow at the station (Kennedy, 1984). A satisfactory control that is stable and sensitive to changing streamflow produces a reliable and accurate stage-discharge relation. Other considerations for site selection that are of equal importance are discussed in Rantz and others (1982, p. 4–6).

The selection of instruments used at a gage, once a site has been selected, is dependent on the purpose of the station, and the design of the gage house is dependent on its location relative to the streambed and the type of instruments it is housing. Typical components at a gage include a stage sensor for determining the vertical position of the water surface, a stage recorder for storing stage readings from the sensor, a telemetry system for transmitting stage data from the recorder to the central database, a reference gage for setting the stage sensor, and at least three reference marks for maintaining gage datum (Sauer and Turnipseed, 2010, p. 2). A reference gage is usually a staff plate or pin installed directly in the stream but independent of the gage structure or attachments. Reference marks are usually pins installed independent of the gage structure, and at least one is high enough to be reachable during a major catastrophic flood (greater than a 200-year recurrence or less than the 0.005 annual exceedance probability). Schematics of various gaging-station configurations are illustrated in Sauer and Turnipseed (2010, figs. 50–53, p. 36–39).

#### Accurate Measurement of Stage

Stage of a stream is the elevation of the water surface above an established datum, and the term stage is commonly interchangeable with gage height. Gage datum is either a recognized datum such as local mean sea level or an arbitrary datum established for the gage. An arbitrary datum should be selected such that only positive stage values are measured to avoid possible confusion in subsequent stage-discharge calculations, and it

should be maintained for the life of the gaging station. Effective stage is the height of the water surface above the stage sensor. If a gaging station has to be relocated, the relation between the new and old datum is defined by differential leveling.

Stage data used for streamflow computation require higher precision and accuracy than stage data used for some design and management applications. Therefore, stage data are measured and stored as instantaneous values rather than averaged values. According to Sauer and Turnipseed (2010, p.3), stage readings are collected at the accuracy of 0.01 foot or 0.20 percent of the effective stage, whichever is larger, for the purpose of determining discharge. Owing to the flashy nature of many Hawaiian streams, stage sensors should be set to record at a maximum interval of 15 minutes and a shorter interval during high-flow events. Independent stage readings from a reference gage are used to set the stage sensor and to ensure that data from the stage sensor accurately represent the stage in the stream.

### Routine Differential Leveling

Vertical movement of components at a continuous station may cause inaccurate stage readings. Inaccurate stage readings lead to errors in the computed continuous-streamflow record. Differential leveling is conducted when differences in gage readings are unresolved, stations may have been damaged, stations are relocated, or stations are newly installed and at least every 3 years thereafter (or at other pre-determined frequency). Standard procedures for differential leveling are described in Kenney (2010), and an illustration of differential leveling is in Kenney (2010, fig. 1, p.2). Along with reference and auxiliary gages, the relative altitudes of reference marks are also surveyed during differential leveling. The closure error for a leveling circuit is computed using equation 5 in Kenney (2010).

## Satisfactory Direct-Discharge Measurement

Stream discharge is generally computed as the product of flow velocity and flow area in a measurement cross section. A common and practical method of measuring stream discharge that the USGS uses is the velocity-area method (Turnipseed and Sauer, 2010, fig. 1, p. 2–3). In this method, the width of the stream is divided into subsections (using observation verticals) where width, depth, and average velocity are measured. Total discharge at the measurement section is the sum of the discharges in each subsection.

Factors that affect the accuracy of a discharge measurement may include (1) condition of the measuring instruments, (2) characteristics of the measurement cross section, (3) number and spacing of observation verticals in a measurement cross section, (4) measurement of width, depth and velocity, and (5) changing stage during the measurement (Rantz and others, 1982, p. 179–180). To make reliable and accurate discharge measurements, data-quality control standards are recommended to reduce potential errors caused by these factors. A majority of these quality-control standards also apply to direct-discharge measurements made at a partial-record station and seepage-run site.

*Condition of the measuring instruments.*—Flow velocity is typically measured either by mechanical current meter or acoustic velocity meter. Proper operation of the meters requires careful transport and appropriate assembly of the meters, installation of the most current firmware, familiarity with the use of the meters, and instrument tests prior to each field trip and discharge measurement. Pre-field routine check of the meters includes inspecting attached components and battery compartment, reviewing maintenance records, adjusting internal clock and time, and verifying data-collection units and sampling method. For a mechanical current meter, the instrument test consists of a spin test during which the rotor is manually spun and the time until it returns to a resting position is measured. This test is conducted on a stable and level surface to check operation of the rotor. The minimum acceptable times for a spin test are 45 seconds for a Price pygmy meter and 2 minutes for a Price AA meter (Turnipseed and Sauer, 2010, p. 51). For an acoustic velocity meter, instrument test consists of a check of the internal system performance, such as the signal-to-noise ratio, which measures the strength of the reflected acoustic signal relative to the ambient noise level of the instrument (Turnipseed and Sauer, 2010, p. 58).

*Characteristics of the measurement cross section.*—An ideal measurement cross section lies within a reasonably straight reach; has relatively uniform flow, where the direction of flow is perpendicular to the cross section; and has depths and velocities that are within the measurement range of the meter being used (Turnipseed and Sauer, 2010, p. 8). Heavy aquatic growth, unstable streambed (sand or silt), and large obstructions in and surrounding the cross section may cause flow direction and velocities to deviate from those of an ideal cross section, potentially introducing errors into the discharge measurement. Measurement section for a continuous station should be fairly close to the station control to avoid the effect of any inflows or outflows between the measurement section and the control, and to avoid the effect of any channel storage between the measurement section and the control during changing stage (Turnipseed and Sauer, 2010, p.8). Whereas it is often impossible to meet all criteria of an ideal cross section, the field personnel must exercise judgement in selecting the best cross section available to make the discharge measurement.

*Number and spacing of observation verticals.*—Making a discharge measurement is, in effect, a sampling process in which the accuracy of the sampling result (total discharge) typically increases with the number of samples (number of verticals). The accuracy of a discharge measurement may decrease when the number of verticals is less than 25. Therefore, width, depth, and average velocity generally are measured at a minimum of 25 verticals when making a discharge measurement. Discharge computed for each vertical should not exceed 10 percent of the total discharge and ideally not exceed more than 5 percent (Rantz and others, 1982, p. 140). To achieve a satisfactory balance in the number and spacing of verticals, the spacing of the verticals should be closer in parts of the measurement cross section that have greater depths and velocities.

*Measurement of depth and velocity.*—The width and depth of a vertical, typically made as wading measurements, are measured with a tagline and a top-setting wading rod, respectively. A tagline is a measuring tape in tenths of feet for measuring width of a vertical. A wading rod is used to secure the mechanical current meter or acoustic velocity meter, and contains an integrated scale to measure depth of a vertical. The minimum width between verticals when making a discharge measurement differs with the type of instruments used. When measuring the stream depth in a vertical, the wading rod must be placed securely on the streambed, and in sandy or silty streambeds the wading rod must be supported to avoid sinking the wading rod into the streambed. When water velocities are high, stream depth is determined by measuring where the water surface intersects the wading rod and not where the velocity-head buildup of water intersects the wading rod (Turnipseed and Sauer, 2010, p. 9 and 12). For shallow depths of 1.5 feet or less, the measuring instrument is placed at a depth of 0.6 of the distance from the water surface to the streambed, where average velocity is expected to occur. For deeper verticals, the average velocity is typically estimated by measuring velocities at the 0.2 and 0.8 depths from the water surface to the streambed. Where flow is not perpendicular to the measurement section, the velocity measured at a vertical is adjusted to account for flow angle, and the adjustment is made internally by an acoustic velocity meter.

*Changing stage during the measurement.*—The appropriate stage reading to apply to a discharge measurement is subject to some uncertainty when the discharge measurement is made during changing stage. During periods of changing stage, the time it takes to make a discharge measurement should be shortened by measuring velocity at one location within the vertical (typically at the 0.6 depth), reducing the velocity-observation time (typically from 40 seconds to 20 seconds), and (or) reducing the number of observation verticals. The reduction in measurement time may decrease the accuracy of the discharge measurement; however, it allows the calculation of a mean weighted gage-height reading that is representative of the measured discharge. This is particularly important for the development of a stage-discharge relation at a continuous gaging station.

For many years the USGS has been using a quasi-quantitative method of evaluating discharge measurements based on the factors that could potentially affect the accuracy of the measurement (Sauer and Meyer, 1992, p. 2). The resulting measurement is given one of four ratings—excellent, good, fair, or poor. Discharge measurements rated excellent are considered to be within 2 percent of the actual discharge, good are within 5 percent of the actual discharge, fair are within 8 percent of the actual discharge, and poor are greater than an 8 percent difference from the actual discharge. Sauer and Meyer (1992) proposed a procedure for quantifying the overall discharge-measurement error for measurements made by the velocity-area method using mechanical current meters. This procedure forms the basis for calculating the overall error in measurements made with an acoustic velocity meter, which has become the more widely used instrument within the USGS for making discharge measurements.

The measurement rating of discharge measured with an acoustic velocity meter using the velocity-area method is based on the interpolated variance estimator (IVE) computed by the meter. The IVE is an estimator of all random sources of uncertainty, and it is based on a statistical analysis of depth and velocity data collected during the discharge measurement rather than using results from empirical experiments that may not be representative of on-site conditions (Cohn and others, 2013). Discharge measurements with an IVE value of 2 percent or less are generally rated excellent, 5 percent or less are rated good, 8 percent or less are rated fair, and more than 8 percent are rated poor. Errors that result from changing flow conditions are not considered by the IVE. The field technician may choose to downgrade the rating of a measurement owing to changing stage, the condition of the measuring instrument, and other environmental factors.

### Indirect-Discharge Measurement

Streams in Hawai‘i generally have small drainage areas and are characterized by rapid rise and fall of streamflow. Peak discharge measurements are important for defining the upper sections of the stage-discharge relation at a continuous-record streamflow-gaging station. Indirect methods are typically used to compute discharges during periods of high flows when physical access to the measurement site during the high-flow event may not be feasible, personnel are not given sufficient warning to reach the measurement site to make a direct-discharge measurement, or stage is changing rapidly that a reliable direct-discharge measurement could not be made.

The indirect method used—for example, slope-area method (Dalrymple and Benson, 1986), critical-depth computations (Hulsing, 1967), culvert computations (Bodhaine, 1982), step-backwater computations (Arneson and Shearman, 1998; and U.S. Army Corps of Engineers, 2008)—differs for different types of flow. However, all methods are based on hydraulic equations that relate discharge to the geometry of the stream channel and water-surface profile at the time of the peak discharge (Rantz and others, 1982, p. 273). Geometry of the stream channel can be informed through cross-sectional surveys of the stream channel. Water-surface profile data are obtained through flagging and surveying of high-water marks, and crest-stage stations facilitate the determination of high-water marks.

Data-collection and computation procedures for various indirect methods of determining discharges are presented in Rantz and others (1982) and Benson and Dalrymple (1967). The latter report includes policies and procedures related to site selection, field survey, identification of high-water marks, and the selection of channel roughness coefficients, all of which help to control the quality of the data collected and reduce errors in the computed discharges.

## Groundwater

In addition to time and geographic location discussed earlier in this section, the groundwater-monitoring program

collects two other types of data—groundwater levels and specific conductance. Quality needs for each of these data types are discussed in the following subsections. Quality needs for altitude are also discussed because anticipated analyses of the water-level and specific-conductance data require tying the data from multiple wells to a common datum, such as sea level.

## Water Level

Manual water-level measurements are required for all groundwater monitoring discussed in this report, regardless of whether the site has instruments for automated continuous measurements or is used for specific-conductance profiling. Water level must be measured to a precision of at least 0.01 ft to facilitate analysis of the gentle water-table gradients in some hydrologic settings in Hawaiʻi, such as the high permeability aquifers with freshwater lenses where gradients can be less than a foot vertically per horizontal mile. Drawdowns of pumped wells in the high-permeability settings commonly are a fraction of a foot, especially at distances from the well where they can affect groundwater discharge to streams and the coast.

Manual water-level measurements are made by lowering a measuring tape into a well. The distance from an established measuring point (MP) to the top of the water in the well is called the depth to water (DTW). Measuring DTW from the same MP ensures that data taken at different times are comparable. An established MP is typically a point at the top of the well, such as a spot on the top of the well casing that can be easily accessed by the tape each time a measurement is made. Because the top of the well casing may not be precisely horizontal, one point on the casing is permanently marked and used consistently as the MP. Although MPs are established with the goal of being relatively permanent, they may be destroyed during the course of monitoring. Establishing nearby altitude reference marks at the onset of monitoring and determining the relative altitude between the MP and reference marks will ensure that if the original MP is destroyed, a new MP can be established, and subsequent measurements can be tied to measurements made relative to the original MP.

The standard USGS procedure for measuring groundwater level uses a steel tape (Koterba and others, 1995). Water level can also be measured using an electrical tape (a plastic tape with wires and an electronic sensor at the end that emits an audible or visual signal when the sensor touches water), but the pliable tapes are susceptible to stretching or other deformation that can result in measurement inaccuracies. Even with the more-durable steel tape, careful handling and proper maintenance are needed to ensure that twists, kinks, and other abuse will not result in measurement inaccuracies. In addition, periodic calibration checks are needed to ensure that the accuracy of the steel tape is maintained over time.

Water levels can also be measured using automated instruments, including float-with-shaft-encoder systems and pressure-measuring systems. Float-with-shaft-encoder systems translate the movement of a float on the water surface in a well to angular rotation on a wheel of a shaft encoder, which then sends electronic signals to a data logger. In pressure-sensing systems, sensors are positioned below the water surface in a well and measure pressure variations, which are related to the height and density of water above the pressure sensor and to pressure exerted on the water surface by the atmosphere. Pressure measured by the device can be converted to depth of submergence (and then to DTW) provided water density (varies with salinity) is accounted for and atmospheric-pressure variations (unrelated to water level) are eliminated.

The raw output signal of a device (angular rotation or pressure) is converted to a length (for example, DTW or water level) measurement. Monitoring protocols must ensure that the raw output has the precision that meets the purposes of water-level monitoring, and eliminate or account for other factors that can cause data variations unrelated to water levels. Instrument accuracy is ensured by calibration before initial installation and subsequent periodic calibration checks for instrument drift. Manual water-level measurements are required during the installation of automated instruments to tie the instrument's data to the MP, and periodic measurements are made to verify that the instruments are operating properly while in place.

## Specific Conductance and Temperature

Specific conductance of water is a measure of the ability of a standard volume of water at a standard temperature to conduct electricity. Conductance is commonly used as an indicator of salinity because it is relatively easy to measure and requires no sampling or laboratory analysis. For dilute solutions such as natural groundwater, specific conductance is commonly expressed in units of microsiemens per centimeter at 25 degree Celsius (µS/cm at 25 ºC). Because temperature is integral to the specific-conductance measurements, many specific-conductance probes that measure electrical conductance of fluids also measure temperature and automatically convert the electrical-conductance readings to specific conductance. Some probes (commonly referred to as CTDs), simultaneously measure conductance, temperature, and depth.

A probe that measures specific conductance can be lowered down a DMW that penetrates through a transition zone to log the variation in specific conductance with depth from freshwater above to saltwater below. Specific conductance measured in freshwater will often be less than 1,000 µS/cm at 25 ºC, whereas specific conductance in seawater is about 50,000 µS/cm at 25 ºC (Hem, 1985); probes spanning this range with two to three significant figures are required for the uses of specific-conductance profiling anticipated for meeting State monitoring needs.

The fundamental parameters measured by specific-conductance probes are electrical conductance and temperature, and a probe's accuracy for measuring these parameters must be checked periodically. Measurement accuracy of specific conductance is maintained by periodic checks against laboratory-sourced standard solutions that have known specific conductance and by adjusting probe calibration, if necessary, according to the manufacturer's instructions. Measurement accuracy of temperature is maintained by periodically comparing a probe's

temperature readings, at several points within the instrument's operational range, against temperature readings of a thermometer certified by NIST. Temperature accuracy within 0.2 ºC is required for the monitoring discussed in this report.

Accurate measurement of the depth, relative to the MP, of a probe's electrical-conductance sensor is also integral to specific-conductance profiling. Many well-logging systems have a device to measure the length of cable deployed as a sensor is lowered into a well; if the accuracy of the device can be verified and its readings can be related to the MP, the device can provide depth of the sensor. Alternatively, for shallow wells, the cable used to lower the probe can be marked accurately at certain intervals of length, which can be held against the MP to determine the probe's depth. As with using the steel tape for making water-level measurements, periodic calibration checks are needed to ensure that the accuracy of the length markings on the cable are maintained over time.

If the probe is a CTD, a second method of determining the electrical-conductance sensor's depth relative to the MP is to calculate the depth of submergence from the probe's pressure-sensor data. Depth of submergence can be converted to depth below MP by adding DTW determined by a nearly concurrent manual water-level measurement. This approach for determining depth can be problematic because DTW can change over the time it takes to conduct a specific-conductance profile. Also, the relation between pressure and depth depends on the density of the water, which in turn depends on salinity and temperature. As with using pressure sensors for monitoring water levels, the accuracy of the CTD's pressure sensor must be periodically checked, and pressure variations caused by factors unrelated to depth of submergence, such as variations in atmospheric pressure or water density, must be eliminated.

### Absolute Altitude

Where groundwater-monitoring data collected at multiple wells are used in an areal analysis (as in a synoptic survey), the wells in the analysis must be tied to common altitude (vertical) datum to allow comparison of data. For oceanic islands such as Hawaiʻi, the vertical datum for groundwater-monitoring data is usually local mean sea level. Tying the measurements, such as DTW and depth in specific-conductance profiles, of individual wells to the common sea-level datum requires differential leveling to points of known altitude to determine the altitude of all MPs relative to local mean sea level.

## Limitations

This report describes monitoring programs to provide long-term rainfall, surface-water, and groundwater data for water-resource management and increased understanding of climate change. The programs are for monitoring at the statewide scale and cannot anticipate all issues that may arise that require more intensive monitoring in specific areas and study periods. The greater monitoring-site density and higher measurement frequency commonly required to address these issues are not feasible on a statewide scale.

Placement of surface-water and groundwater monitoring sites, identified for the monitoring program, focused on priority areas determined in collaboration with CWRM and County water departments in the State. Some non-priority areas that are not currently monitored and have little or no historical data will remain unmonitored. Other considerations, such as the need for baseline data, may warrant the placement of monitoring sites even in non-priority areas.

Monitoring of the perched-groundwater setting is not considered in this study. Although some high-altitude water bodies are postulated to be associated with perched-groundwater settings and may provide water for human and environmental needs, confirmation of the perched-groundwater setting is problematic. Confirmation of the perched-groundwater condition can be the subject of focused studies separate from the long-term monitoring considered in this study.

The water-resource monitoring program described likely will need to be reevaluated as new water-resource and hydrologic issues emerge in the future. The associated data-collection strategies and data-quality objectives will need to be modified accordingly to ensure accurate and reliable hydrologic data that are appropriate for addressing the new objectives. The islands of Niʻihau and Kahoʻolawe were excluded from the study scope but may be included in future assessments as water-resource needs are identified.

This report does not include a plan to implement the monitoring program, which would be useful for targeting available funds to install, operate, and maintain a list of prioritized monitoring stations through a multi-year program. The implementation plan will need to be developed in consultation with the CWRM, WRRC, County water departments, and other stakeholders. The plan should include preliminary cost estimates based on current dollars for the installation, operation, and maintenance of data-collection sites in the monitoring programs for rainfall, surface-water, and groundwater monitoring.

A statewide integrated water-data platform that combines existing water-resource and water-use information from multiple agencies and (or) databases would be useful to create and refine decision-support tools in water-resource management. This will be a positive step towards integrated water-resource assessment, management, and protection in Hawaiʻi.

Monitoring for water-quality and flood-hazard issues was not addressed in developing the water-resource management monitoring program. These issues commonly require different strategies and equipment, and more intensive monitoring than is described in this report.

## Summary

An effective monitoring program is a fundamental component of water-resource science and policy. The effectiveness of the monitoring program depends on its spatial and temporal

scale, range of applicability, ability to address current objectives, and adaptability as more water-resource issues arise. The monitoring program should also ensure high data quality, data accessibility, and cost effectiveness of acquiring the data.

This report documents a water-resource monitoring program, specifically a rainfall, surface-water, and groundwater data-collection program, that meets State needs for water-resource assessment, management, and protection in Hawai‘i. Current and future issues related to water-resource management and climate-change effects were identified in collaboration with the State of Hawai‘i Commission on Water Resource Management, University of Hawai‘i Water Resources Research Center, County water departments, and other stakeholders. These issues were used to develop a set of criteria for identifying and evaluating individual monitoring stations needed within the monitoring program and a set of goals the program should achieve.

Data-collection sites were divided into two data-collection networks: (1) a resource-management network to determine effects of water- and land-use changes on surface-water and groundwater resources, and (2) a climate-response network to determine effects of climate change on surface-water and groundwater resources in representative hydrogeologic settings. Using this framework, data-collection sites currently (2018) being operated in Hawai‘i were evaluated for inclusion in the monitoring program. Additional data-collection sites that supplement the current program were identified with consideration given to reactivating discontinued sites with substantial historical data. Data-collection strategies associated with the data-collection sites consist of a combination of continuous long-term and occasional intensive monitoring to evaluate trends and climate-change effects and to enhance spatial understanding of hydrologic conditions and address current issues in priority areas, respectively.

The rainfall-monitoring program focuses on achieving a representative spatial distribution to maximize coverage of rainfall priority areas across the islands by reactivating rain gages with historical datasets. Rainfall priority areas include urban and agricultural lands, areas with high rainfall and high-rainfall gradient, and areas within the trade-wind inversion band. In addition to the 381 active rain gages, the monitoring program includes 173 additional rain gages that would increase effective rain-gage coverage by more than 20 percent of land area and more than 25 percent of rainfall priority areas. Although Lāna‘i had the lowest effective active rain-gage coverage, the high spatial and temporal variations in rainfall occurring on Hawai‘i island make it the most under-represented in current rainfall coverage; therefore, more than half of the additional rain gages were selected for Hawai‘i island.

The resource-management network of the surface-water monitoring program focuses data collection on streams with major surface-water diversions, with established interim instream-flow standards, that are in a surface-water management area, and that support water leases. The climate-response network generally includes active continuous stations with long-term records of unregulated flow for determining streamflow characteristics and analyzing long-term streamflow trends and groups of additional continuous and partial-record stations for describing regional hydrologic characteristics. The monitoring program includes an additional 46 continuous stations and 14 partial-record stations to supplement the current monitoring program to address State needs.

Evaluation of groundwater-monitoring priorities was based on management of groundwater resources and assessing the response of aquifers to climate changes. The resource-management network of the groundwater-monitoring program focuses monitoring in areas with current or anticipated issues, such as high withdrawal, declining water levels, reduced groundwater recharge, limited alternative sources, and uncertainties in hydrogeologic characteristics. The goal of the climate-response network is to monitor the full range of hydrogeologic and climate settings in Hawai‘i through long-term water-level monitoring and specific-conductance profiling. To meet the objectives of the resource-management and climate-response networks for groundwater, 156 additional long-term monitoring sites and 48 additional specific-conductance profiling sites are needed to supplement the 67 active sites in the State. Synoptic surveys, which are not currently part of the regular groundwater-monitoring program, are identified for 15 areas statewide.

Data-quality objectives consider the precision of, and uncertainties in, measured values, which relate to the reliability of the data for a particular use. Higher data quality generally incurs greater costs, but not all applications require data having the highest possible precision and least uncertainty. Included in this report is a data-quality objectives process discussion that considers the anticipated uses for the data and sets achievable data-quality goals that meet the needs of those uses. This process can be used to evaluate the quality of the data collected by Federal, State, and County agencies and determine whether those data meet program standards. The data-quality objectives cannot anticipate all potential future uses of the data. The key to ensuring that data collected today can be evaluated for unanticipated applications in the future is to provide adequate metadata that describe how the data were collected and what precision, accuracy, and uncertainty are associated with the measurements.

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