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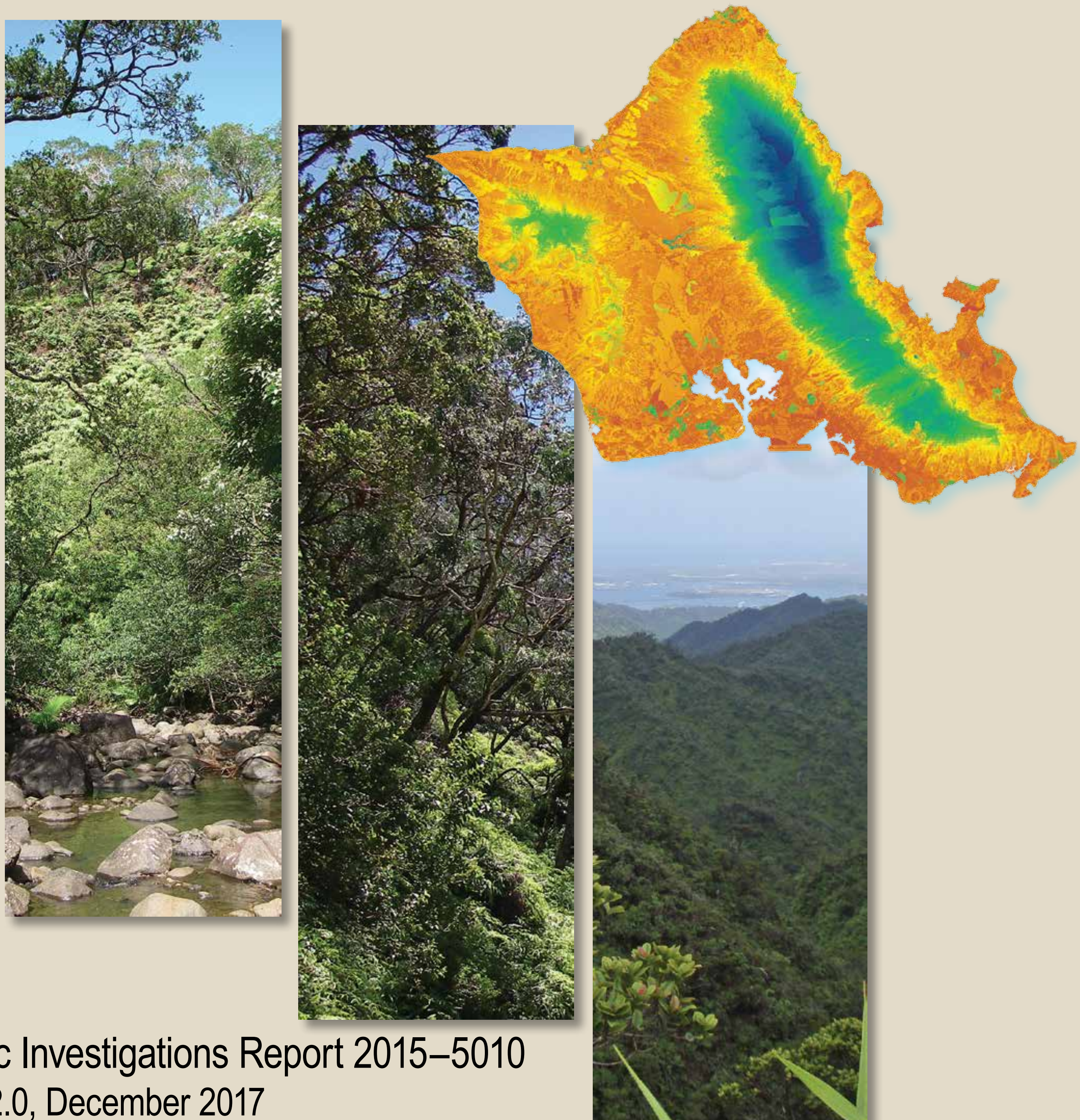
Spatially Distributed Groundwater Recharge for 2010 Land Cover Estimated Using a Water-Budget Model for the Island of O’ahu, Hawai’i



Scientific Investigations Report 2015–5010

Version 2.0, December 2017

U.S. Department of the Interior
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COVER

From left to right. An upper reach of Kīpapa Stream, Island of Oʻahu, Hawaiʻi. Photograph by Reuben H. Wolff, June 2007. Hillside in upper Kīpapa Valley covered with native and alien plants, Island of Oʻahu, Hawaiʻi. Photograph by Reuben H. Wolff, June 2007. View from Waimano Ridge near the crest of the Koʻolau Range looking southwest toward Pearl Harbor, Island of Oʻahu, Hawaiʻi. Photograph by Adam G. Johnson, May 2010. Top right: Mean annual recharge for average climate conditions, Island of Oʻahu.

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U.S. Department of the Interior
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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
million gallons (Mgal)	3,785	cubic meter (m^3)
	Flow rate	
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)

Vertical coordinate information is referenced to mean sea level.

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

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

Acronyms

Acronyms	Meaning
CWRM	State of Hawai‘i Commission on Water Resource Management
ET	Evapotranspiration
TMK	Tax map key
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
WRPP	State of Hawai‘i Water Resource(s) Protection Plan

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Spatially Distributed Groundwater Recharge for 2010 Land Cover Estimated Using a Water-Budget Model for the Island of O‘ahu, Hawai‘i

By John A. Engott,[1] Adam G. Johnson,[1] Maoya Bassiouni,[1] Scot K. Izuka,[1] and Kolja Rotzoll[2]

Abstract

Owing mainly to projected population growth, demand for freshwater on the Island of O‘ahu is expected to increase by about 26 percent between 2010 and 2030, according to the City and County of Honolulu. Estimates of groundwater recharge are needed to evaluate the availability of fresh groundwater. For this study, a water-budget model with a daily computation interval was developed and used to estimate the spatial distribution of recharge on O‘ahu for average climate conditions (1978–2007 rainfall and 2010 land cover) and for drought conditions (1998–2002 rainfall and 2010 land cover). For average climate conditions, mean annual recharge for O‘ahu is about 660 million gallons per day, or about 36 percent of precipitation (rainfall and fog interception). Recharge for average climate conditions is about 34 percent of total water inflow, which consists of precipitation, irrigation, septic leachate, water-main leakage, and seepage from reservoirs and cesspools. Recharge is high along the crest of the Ko‘olau Range, reaching as much as about 180 inches per year in the north-central part of the range. Recharge is much lower outside of the mountainous areas of the island, commonly less than 5 inches per year in unirrigated areas. The island-wide estimate of groundwater recharge for average climate conditions from this study is within 1 percent of the recharge estimate used in the 2008 State of Hawai‘i Water Resource Protection Plan, which divides the Island of O‘ahu into 23 aquifer systems for groundwater management purposes. To facilitate direct comparisons with this study, these 23 aquifer systems were consolidated into 21 aquifer systems. Recharge estimates from this study are higher for 12 of the aquifer-system areas and lower for 9. Differences in mean rainfall distribution and the inclusion of irrigation in this study are the primary reasons for discrepancies in recharge estimates between this study and the 2008 Hawai‘i Water Resources Protection Plan. For drought conditions, mean annual recharge for O‘ahu is about 417 million gallons per day, which is about 37 percent less than recharge for average climate conditions. For individual aquifer-system areas, recharge for drought conditions is about 25 to 70 percent less than recharge for average climate conditions.

Introduction

An updated, island-wide estimate of groundwater-recharge distribution is needed for the Island of O‘ahu, Hawai‘i (fig.1) and is recommended in the State’s Water Resource Protection Plan (WRPP; State of Hawai‘i, 2008). Published almost 20 years ago, the last island-wide estimate of groundwater-recharge distribution was presented in Shade and Nichols (1996), which relied heavily on even older publications that calculated water budgets for southern (Giambelluca, 1983) and southeastern (Eyre and others, 1986) O‘ahu. In addition to advanced computing power and improved geographic information systems (GIS), current water-budget models for the estimation of recharge in the Hawaiian Islands take into account fog interception, canopy evaporation, and direct sources of recharge, such as water-main leakage and cesspool seepage (for example, Engott, 2011), for which no accounting was consistently made in water-budget models prior to the 21st century. Groundwater-recharge estimates can be further improved by using newly available rainfall and evapotranspiration (ET) datasets (Frazier and others, 2016; Giambelluca and others, 2013; 2014). Estimates of recharge are used by the State Commission on Water Resource Management (CWRM) to calculate sustainable-yield values for aquifer systems on the island (fig. 1). Sustainable yield is defined 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 CWRM (State of Hawai‘i, 2008). CWRM periodically reassesses sustainable yields through their update of the WRPP or as updated recharge values and related information become available. Although pumpage from each aquifer system on O‘ahu was generally less than the sustainable yield as of 2008 (State of Hawai‘i, 2008), demand for groundwater is growing as population on the island increases. The City and County of Honolulu projects that freshwater demand will increase from an estimated 164 million gallons per day (Mgal/d) in 2010 to 206 Mgal/d in 2030, an increase of about 26 percent (State of Hawai‘i, 2008). This increased demand likely will be met by increased groundwater pumpage.

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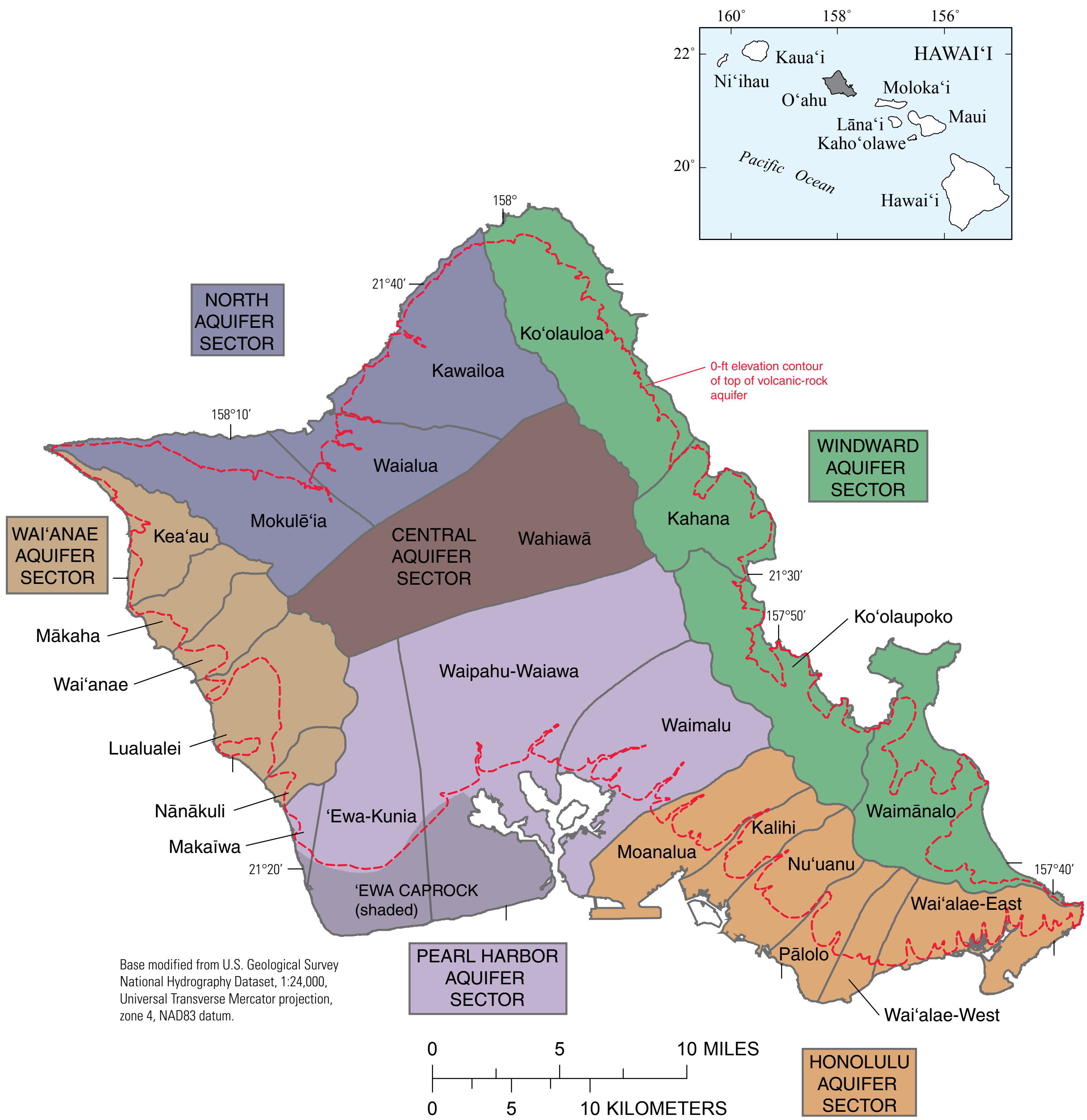

Figure 1. Aquifer systems and sectors on the Island of O‘ahu, Hawai‘i (State of Hawai‘i, 2008).

Purpose and Scope

The purpose of this report is to quantify the spatial distribution of mean annual groundwater recharge for the Island of Oʻahu. To estimate recharge, a water-budget model that uses a daily computational interval is developed. Hydrological processes and physical conditions that affect recharge on Oʻahu are simulated in the water-budget model using the most current data available, including maps of rainfall for each month during 1978–2007 and mean monthly reference grass ET (Frazier and others, 2016; Giambelluca and others, 2013; 2014). The spatial distribution of mean annual recharge is estimated for two scenarios (1) mean climate conditions (1978–2007 rainfall and 2010 land cover), and (2) drought conditions (1998–2002 rainfall and 2010 land cover). Recharge estimates from this study are compared with estimates of mean recharge from previous water-budget studies. Finally, the sensitivity of recharge estimates to selected water-budget components is evaluated.

Previous Studies

A number of previous studies have estimated groundwater recharge for various parts of Oʻahu, with the focus being primarily on southern Oʻahu and the Pearl Harbor area (table 1). Giambelluca (1983) used a highly detailed water-budget approach to estimate recharge for southern Oʻahu. Two groundbreaking aspects of that study were (1) a daily computational interval was used by estimating representative patterns of normalized daily rainfall and irrigation distributions, and disaggregating mean monthly data accordingly; and (2) spatial variation in rainfall and ET was captured by breaking up the study area into smaller zones. Shade and Nichols (1996) mostly used regression models developed from the results of Giambelluca (1983) to estimate recharge for other parts of Oʻahu for predevelopment and mid-1980s conditions. Other studies used water budgets with monthly or annual computational intervals, which can lead to biased recharge estimates (Giambelluca and Oki, 1987; Oki, 2008). In general, uncertainty in recharge estimates is less for water budgets calculated using the shortest computational interval that is consistent with the physical processes being represented (Oki, 2008). The 1990 WRPP (State of Hawaiʻi, 1990) used a water budget with an annual time step to estimate recharge for each aquifer-system on Oʻahu (fig. 1) and the other main Hawaiian Islands. The water budget for this study uses a daily computational interval, which provides a more realistic simulation of rainfall, soil moisture, ET, and recharge. Comparisons of the results of this study with previous studies of recharge on Oʻahu generally are confounded by differences in study periods and areas.

Table 1. Previous groundwater recharge studies for the Island of Oʻahu, Hawaiʻi.

Reference	Area
Safeeq and Fares (2012a)	Mākaha area
Shade and Nichols (1996)	Entire island
State of Hawaiʻi (1990)	Entire island
Eyre and others (1986)	Southeastern Oʻahu
Giambelluca (1983; 1986)	Southern Oʻahu
Broadbent (1980)	Central Oʻahu
Mink (1980)	Southern Oʻahu
Mink (1978)	Waiʻanae area
Takasaki (1971)	Waiʻanae area
Takasaki and others (1969)	Windward Oʻahu
Takasaki and Valenciano (1969)	Kahuku area
Dale (1967)	Pearl Harbor area
Wentworth (1951)	Southern Oʻahu

Acknowledgments

This study was conducted in cooperation with the State of Hawaiʻi Commission on Water Resource Management. The authors thank Abby Frazier and Thomas Giambelluca of the University of Hawaiʻi at Mānoa; Roy Hardy, Lenore Ohye, and Jeremy Kimura of the State of Hawaiʻi Commission on Water Resource Management; and Carolyn Sawai of the Honolulu Board of Water Supply for providing data and information for this report.

Description of Oʻahu

The Island of Oʻahu has an area of about 596 square miles. Oʻahu is the third largest of the Hawaiian Islands and the most populous, with an estimated population of 983,429 in 2013 (State of Hawaiʻi, 2014). Oʻahu is the center of commerce, industry, and government in Hawaiʻi and is the site of the State capital, Honolulu. For groundwater management purposes, CWRM divides the Island of Oʻahu into 6 aquifer sectors and 23 aquifer systems (fig. 1).

Physical Setting

Oʻahu is formed by the eroded remnants of two elongated shield volcanoes with broad, low profiles. Weathering and erosion have modified the original domed surfaces of the volcanoes, leaving a landscape of deep valleys and steep inter-fluvial ridges in the interior highlands. The Koʻolau Range in eastern Oʻahu and the Waiʻanae Range in western Oʻahu (fig. 2) are the eroded remnants of the Koʻolau and Waiʻanae Volcanoes. In central Oʻahu, which forms the saddle between the Koʻolau and Waiʻanae Ranges, erosion has been less severe and has only slightly modified the original domes. A flat coastal plain composed of sedimentary deposits, locally referred to as caprock, surrounds much of Oʻahu. The caprock varies in width from a narrow marine terrace to a broad plain several miles wide.

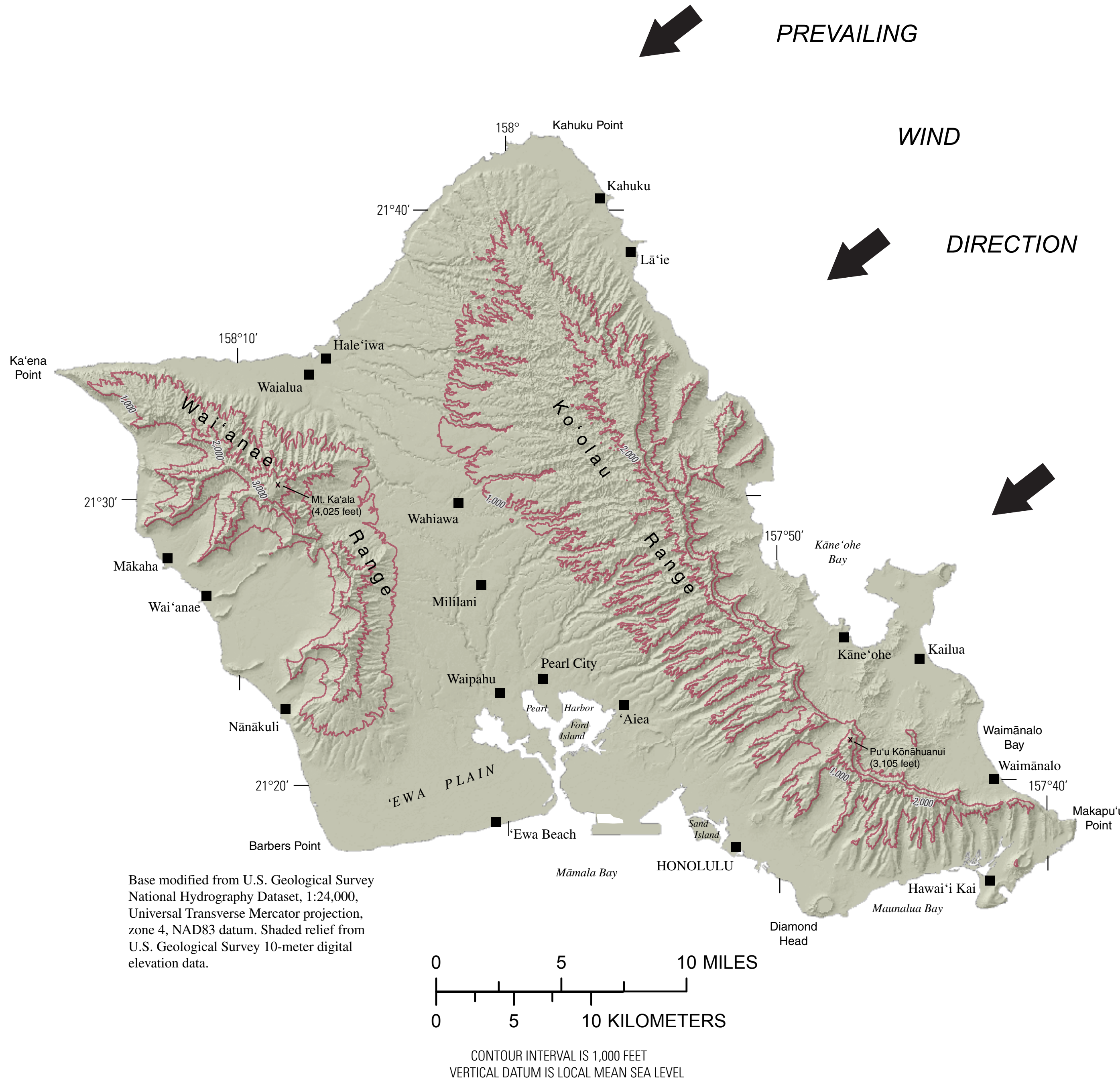

Figure 2. Major towns and geographical features on the Island of O‘ahu, Hawai‘i. Red lines are elevation contours with a 1,000-ft interval.

Climate

Weather patterns in Hawai‘i are affected by the interaction between northeast trade winds and the topography of the Hawaiian Islands (Schroeder, 1993). The Hawaiian Islands are in the path of persistent trade winds that originate from the north Pacific anticyclone, which is a region of high atmospheric pressure usually located northeast of the Islands. Mountains of the Hawaiian Islands obstruct trade-wind airflow and create wetter climates on northeast-facing (windward) mountain slopes and drier climates on southwest-facing (leeward) mountain slopes (Sanderson, 1993). As moist air ascends windward mountain slopes, it cools adiabatically and can form clouds. Persistent trade winds and orographic lifting of moist air result in recurrent clouds and frequent rainfall on windward slopes and near the peaks of all but the tallest mountains of the Hawaiian Islands (Giambelluca and others, 1986). Loss of moisture from air that ascends windward slopes leads to relatively drier climates along leeward slopes in the rain shadow of the mountains.

When trade winds are present, the vertical development of clouds is restricted by the trade-wind inversion layer. Within the trade-wind inversion layer air temperature increases with elevation, whereas the air temperature in regions above and below the inversion layer generally decreases with elevation (Schroeder, 1993). Cao and others (2007) determined the trade-wind inversion layer occurs overall about 82 percent of the time in Hawai‘i and has an average base elevation of about 7,100 ft. The elevation of the inversion, however, varies over time and space and is affected by thermal circulation patterns, such as land and sea breezes (Giambelluca and Nullet, 1991). With a maximum elevation of 4,025 ft (fig. 1), most of O‘ahu is usually immersed in the moist air layer below the inversion.

The variability of weather and rainfall patterns in Hawai‘i during the year is typically described in terms of dry and wet seasons. The dry season (May through September) has warm temperatures and steady trade winds that blow 80 to 95 percent of the time (Blumenstock and Price, 1967; Sanderson, 1993). The wet season (October through April) has cooler temperatures and less persistent trade winds. Statewide storm rainfall is more common during the wet season when low-pressure and frontal systems pass near the Islands (Giambelluca and others, 1986). Much of the rainfall on leeward sides of the Hawaiian Islands comes from these synoptic-scale systems (Schroeder, 1993). Low-pressure systems that develop to the west of the Hawaiian Islands can result in moist, southerly winds and rainfall that may persist for more than a week (Schroeder, 1993). During the early part of 2006, for example, a series of low-pressure systems to the west of the Hawaiian Islands persisted for nearly seven weeks and generated an onslaught of storms that resulted in an unusual extended rainy period across the Islands (Nash and others, 2006).

Steep gradients in mean annual rainfall patterns on O‘ahu reflect the influence of persistent trade winds and orographic rainfall (fig. 3; Giambelluca and others, 2013). Mean rainfall is highest—about 280 in/yr—along the north-central crest of the Ko‘olau Range (figs. 2 and 3), and lowest—about 20 in/yr near the southwestern coast of the island. Only about 17 miles separate these two locations. The Wai‘anae Range, although generally taller than the Ko‘olau Range, receives considerably less rainfall because it mostly lies in the rain shadow of the Ko‘olau Range. The highest point in the Wai‘anae Range and on the island, Mt. Ka‘ala, has a mean rainfall of about 79 in/yr. The central saddle of O‘ahu receives about 30 to 40 in/yr of rainfall on average.

Hydrogeology

O‘ahu is primarily formed by layers of shield-stage lava flows from the older Wai‘anae Volcano to the west and the younger Ko‘olau Volcano to the east, and secondarily by preshield-, postshield-, and rejuvenated-stage volcanism (Langenheim and Clague, 1987). Each volcano has two primary rift zones and a third lesser rift zone, all emanating from a collapsed caldera. The layers of lava flows are intruded in places by dikes, which consist of dense, low-permeability rock that formed when magma supplying lava flows solidified in narrow, near-vertical fissures below the ground surface. The dikes and the rocks they intrude are collectively referred to as dike complexes. In the central part of a rift zone, there can be as many as 1,000 dikes per mile of horizontal distance across the zone (Takasaki and Mink, 1985). The number of dikes decreases toward the outer edges of a rift zone. Deposits of terrestrial and marine sediments and reef limestone form a coastal plain of varying width along the shore of O‘ahu. The coastal plain extends more than 5 mi inland near Pearl Harbor. The onshore thickness of the coastal deposits generally is greatest at the coast and thins in an inland direction (Palmer, 1927; Palmer, 1946; Wentworth, 1951; Visher and Mink, 1964; Dale, 1978). The sedimentary wedge is more than 1,000-ft thick along the southern coast near the entrance to Pearl Harbor.

Within the dike-free flank lavas, fresh groundwater occurs in a lens-shaped body underlain by saltwater from the ocean. Between this freshwater lens and the underlying saltwater is a zone of mixing containing brackish water. Natural discharge from the freshwater-lens system generally occurs as diffuse seepage near the coast.

The permeability of volcanic rocks varies and depends on the type (lava flows, intrusive dikes, or pyroclastic deposits), amount of weathering, and the thickness of the rocks. The permeability of the subaerial, shield-building, dike-free lava flows on O‘ahu is generally high. The regional horizontal hydraulic conductivity of the dike-free volcanic rocks typically ranges from hundreds to thousands of feet per day (Soroos, 1973; Mink and Lau, 1980; Hunt, 1996). Because of the high permeability of the dike-free volcanic rocks, horizontal water-table gradients in these rocks are small (on the order of 1 ft/mi). In general, the vertical hydraulic conductivity of the dike-free lava flows may be hundreds of times less than the horizontal hydraulic conductivity. On the basis of a numerical-model analysis of the Pearl Harbor area, Souza and Voss (1987) estimated the ratio of horizontal to vertical hydraulic conductivity to be 200 to 1. Dikes that intrude the lava flows impede the flow of groundwater and reduce the overall permeability of the aquifer. Estimated bulk hydraulic conductivity of dike complexes can be several orders

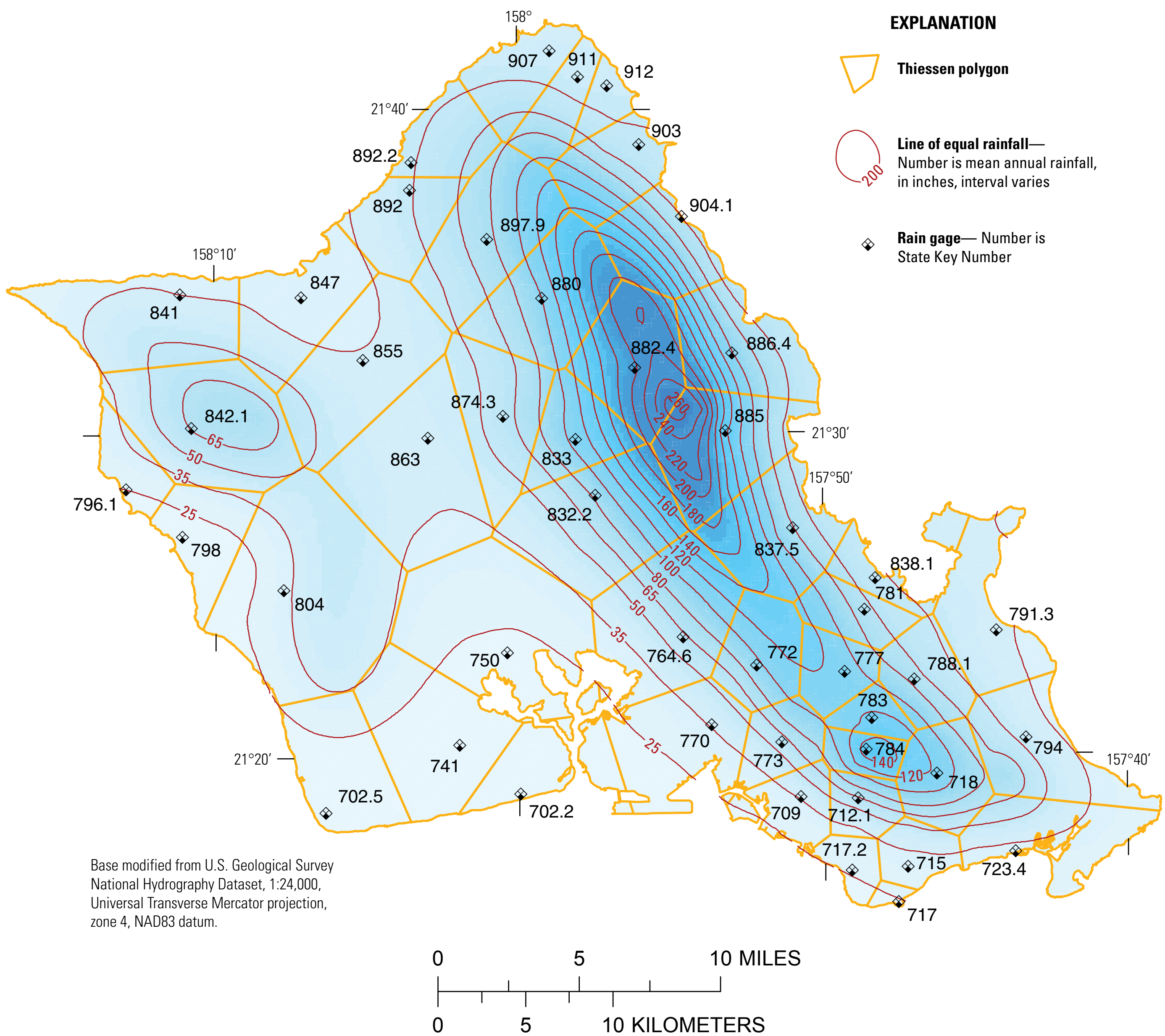

Figure 3. Mean annual rainfall for 1978–2007 (modified from Giambelluca and others, 2013) and locations of rain gages used in the water-budget calculations, Island of O‘ahu, Hawai‘i.

of magnitude lower than that of dike-free flank lavas (Oki, 1999). Other rocks and structures, such as ash layers, soil and weathered rock, unusually thick lava flows, and lava-draped faults, may also form low-permeability features within the otherwise high-permeability lavas of the shield volcano (Stearns and Macdonald, 1946; Oki, 1999). These low-permeability features can increase the thickness of the freshwater lens on the upgradient side of the feature. In dike complexes, highly permeable volcanic rocks can be compartmentalized and groundwater impounded (Stearns and Macdonald, 1946). Groundwater levels in parts of the rift zone of the Ko‘olau Volcano may be as high as 1,000 ft above sea level.

The sedimentary deposits and underlying weathered volcanic rocks of the coastal plain form a low-permeability confining unit, called caprock, that overlies high-permeability volcanic rocks and impedes the seaward discharge of freshwater from the volcanic-rock aquifers. Although the permeability of the various components of the coastal caprock may vary widely, from low-permeability older alluvium and saprolite to cavernous limestone deposits with a hydraulic conductivity of thousands of feet per day, the overall effect of the caprock is one of low permeability (Visher and Mink, 1964), increasing the thickness of the freshwater lens in the volcanic-rock aquifer upgradient of the caprock.

Surface Water

Streams on O‘ahu are short, with steep gradients and small drainage areas. Main courses of streams generally follow the consequent drainage pattern established on the original domed surfaces of the shield volcanoes. Lower-order tributaries branch off from the main courses in a dendritic pattern. Steep terrain and steep stream gradients cause water to run off rapidly following precipitation. As a result, streamflow is characteristically flashy, with high flood peaks. Few streams are perennial over their entire reach. Streamflow is perennial at (1) high elevations where precipitation is persistent and streams intercept dike-impounded or perched groundwater, and (2) near sea level where streams intercept shallow groundwater. These conditions limit surface-water development on O‘ahu and lead to heavy reliance on groundwater for potable supply.

Soils

Factors influencing soil conditions in the Hawaiian Islands include parent material, duration of weathering, climate, topography, and drainage conditions (Macdonald and others, 1983). The ability of a particular soil to absorb and store water affects direct runoff, evapotranspiration, and recharge. Properties of a soil that control its ability to absorb and store water include (1) soil texture, the relative percentages of sand-, silt-, and clay-sized particles, (2) porosity, a measure of how much water a soil can hold, and (3) permeability, a measure of a soil’s ability to transmit water. Slope, vegetation, and soil-moisture content can also affect a soil’s ability to absorb water.

The U.S. Department of Agriculture (USDA) produced a map of soils on O‘ahu (USDA, 2006a) that classifies the soils and land into 160 soil-map units. Soil properties were estimated to depths of 60 inches for most soils. Estimates of available water capacity, the quantity of water that a soil is capable of storing for use by plants, range between 0 and 0.40 inches of water per inch of soil. Areas containing soil horizons with reported zero available water capacity in the top 40 inches of soil include the steep slopes of the windward Ko‘olau Range and the steep upper valleys of the Wai‘anae Range. In general, soil horizons with zero available water capacity are associated with bedrock. Steep slopes may have thin soils overlying bedrock owing to erosion removing soil as fast as it forms (Macdonald and others, 1983).

Land Cover

Patterns of existing vegetation and land cover on O‘ahu reflect the influence of steep climate gradients, decreasing agricultural production, and urban development. Approximately 43 percent of O‘ahu is covered by forests (table 2; U.S. Geological Survey, 2010). Large tracts of forest, generally dominated by the native canopy species *Metrosideros polymorpha* (‘ōhi‘a lehua), exist in the wetter, high-elevation areas of the Ko‘olau Range, with shrubland and grassland in the drier lower elevation areas (fig. 4). Fern species such as *Dicranopteris linearis* (uluhe) dominate wet, windward ridges. Small wetlands exist in some of the flat summits of old volcanic craters, such as Mt. Ka‘ala.

During the 1800s, demand for firewood, commercial logging, agricultural and pasture land conversion, effects of grazing and browsing ungulates, and increased fire frequency resulted in a substantial forest decline on all Hawaiian Islands (Woodcock, 2003). As a result, forest reserves were established in the early 1900s and millions of alien trees were planted by the 1930s. These dramatic changes in land cover may have affected groundwater recharge and base flow (Bassiouni and Oki, 2013). Today (2014), alien forest covers large areas at the middle and low elevations of the Ko‘olau Range and nearly the entirety of the Wai‘anae Range, and invasive species continue to replace native forests in many areas.

During most of the 20th century, the gently sloping lands of central O‘ahu between the Wai‘anae and Ko‘olau Ranges and the ‘Ewa Plain (fig. 2) were dominated by sugarcane and pineapple fields and irrigated by large stream diversions and pumped groundwater. The demise of the sugarcane industry began in the 1980s, and was complete by 1995. Pineapple has been continually cultivated in central O‘ahu since the late 19th century, although to a far lesser degree today than previously. Former sugarcane and pineapple lands that have not converted to diversified agriculture or been developed have become dominated by mostly alien grassland. About 29 percent of O‘ahu is urban development (table 2; U.S. Geological Survey, 2010), with major concentrations occurring in the Honolulu, Pearl Harbor, and Kāne‘ohe/Kailua areas. Since about 1980 and coinciding with the demise of the sugarcane and pineapple industries, new urban development generally has been focused on the ‘Ewa Plain and in central O‘ahu.

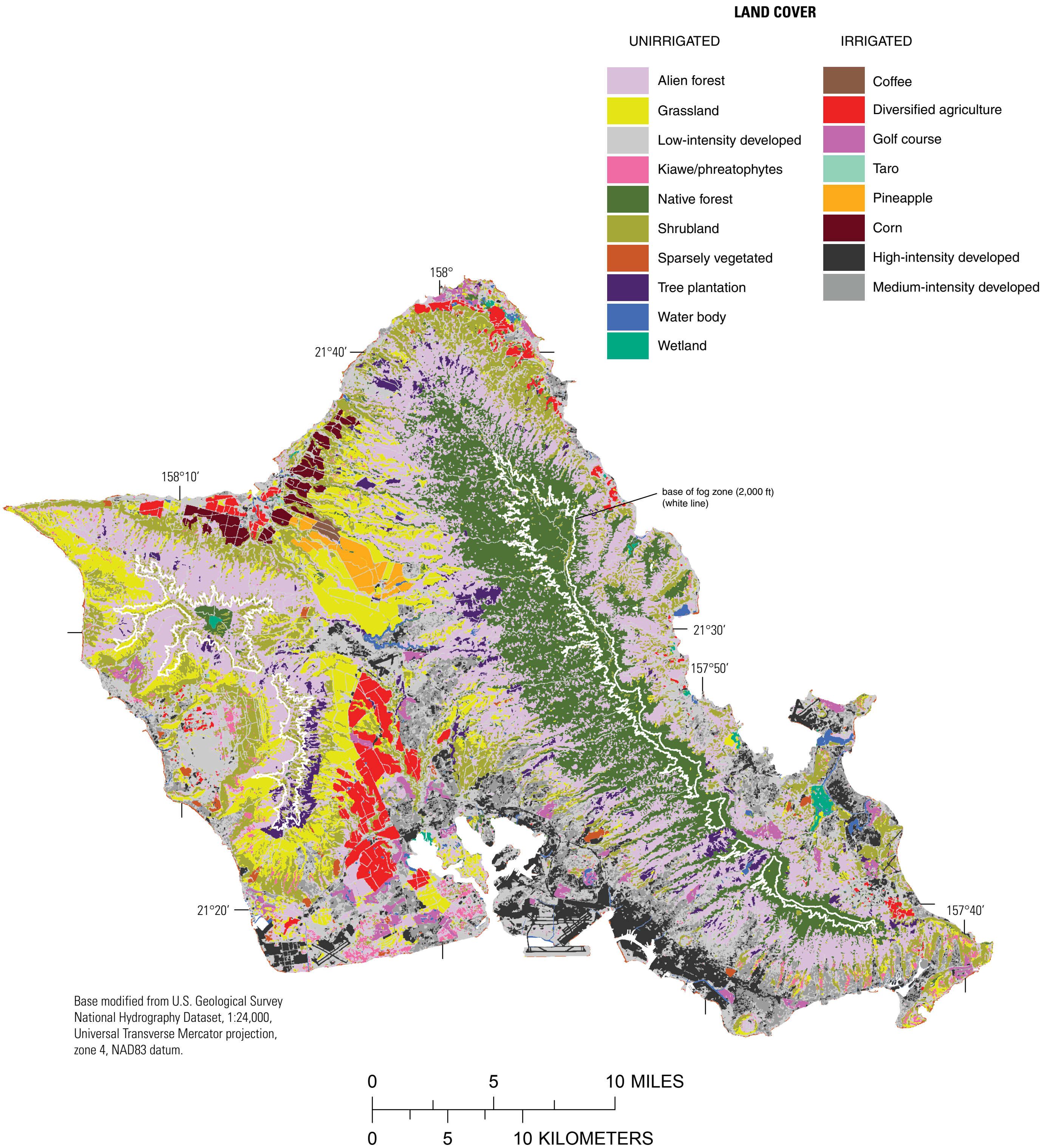

Figure 4. Generalized land cover on the Island O‘ahu during 2010 (modified from U.S. Geological Survey, 2010). Reservoirs and taro are difficult to see at this scale.

Table 2. General types of land cover, as a fraction of aquifer-system area, Island of O‘ahu, Hawai‘i.

[See fig. 1 for location of aquifer systems. See figure 4 for a map of land cover. Agriculture–irrigated consists of coffee, corn, diversified agriculture, pineapple, and taro land covers; Alien forest includes kiawe/phreatophytes and tree plantation; Other consists of sparsely vegetated, reservoir, water body, near-coastal or estuarine water body, and wetland land covers]

Aquifer system	Agriculture–irrigated	Developed and golf course	Grassland	Shrubland	Alien forest	Native forest	Other
Pālolo	0.00	0.63	0.01	0.05	0.14	0.14	0.03
Nu‘uanu	0.00	0.54	0.00	0.01	0.26	0.17	0.01
Kalihi	0.00	0.50	0.00	0.02	0.32	0.17	0.00
Moanalua	0.00	0.58	0.00	0.04	0.20	0.16	0.01
Wai‘alae-West	0.00	0.46	0.02	0.04	0.27	0.20	0.01
Wai‘alae-East	0.00	0.37	0.05	0.20	0.29	0.08	0.01
Waimalu	0.00	0.36	0.01	0.05	0.22	0.36	0.01
Waipahu-Waiawa	0.11	0.37	0.07	0.08	0.19	0.17	0.01
‘Ewa-Kunia	0.05	0.30	0.19	0.16	0.27	0.00	0.02
Makaīwa	0.00	0.22	0.37	0.22	0.11	0.00	0.07
Nānākuli	0.00	0.17	0.33	0.20	0.30	0.00	0.00
Lualualei	0.02	0.35	0.11	0.23	0.27	0.00	0.02
Wai‘anae	0.01	0.23	0.17	0.29	0.28	0.01	0.01
Mākaha	0.00	0.21	0.11	0.27	0.37	0.02	0.02
Kea‘au	0.00	0.05	0.41	0.19	0.33	0.00	0.02
Mokulē‘ia	0.08	0.11	0.06	0.24	0.48	0.03	0.01
Waialua	0.23	0.18	0.24	0.14	0.15	0.05	0.01
Kawailoa	0.05	0.14	0.06	0.15	0.39	0.20	0.01
Wahiawā	0.03	0.17	0.15	0.06	0.27	0.31	0.01
Ko‘olauloa	0.06	0.16	0.01	0.22	0.30	0.23	0.01
Kahana	0.00	0.10	0.01	0.16	0.42	0.30	0.02
Ko‘olaupoko	0.00	0.35	0.01	0.10	0.30	0.22	0.01
Waimānalo	0.01	0.44	0.01	0.16	0.21	0.10	0.06
Island of O‘ahu (all aquifer systems)	0.04	0.29	0.08	0.13	0.27	0.16	0.02

Water-Budget Model

Groundwater recharge replenishes aquifers and is mainly fed by precipitation and irrigation that infiltrates the ground surface and percolates beyond the root zone in the soil. For this study, spatially distributed mean annual groundwater recharge on O‘ahu is estimated using a water-budget model. The water-budget model is designed to simulate—on a daily basis—the hydrological processes and physical conditions that affect recharge on O‘ahu. Hydrological processes simulated by the model include rainfall, fog interception, irrigation, direct runoff, and ET. Physical conditions are represented using parameters that include the moisture-storage capacity of soils and properties of the vegetation and land cover that affect ET.

The water-budget model used for this study is a modified version of the models used for previous U.S. Geological Survey (USGS) recharge studies for various parts of Hawai‘i (Oki, 2002; Izuka and others, 2005; Engott and Vana, 2007; Engott, 2011; Gingerich and Engott, 2012). The structure of the model used for this study is similar to that of the earlier models. The model used for this study differs from previous versions of the model by covering the entire Island of O‘ahu, and using more current maps of rainfall, land cover, and reference grass ET. Additionally, the model used for this study includes more robust methods for (1) using streamflow records to estimate the spatial distribution of direct runoff, and (2) quantifying precipitation that is intercepted by, and evaporates from, forest canopies.

The water-budget model used for this study is similar to other models that simulate a root-zone water balance and can be used to estimate recharge (for example, Leavesley and others, 1983; Hevesi and others, 2002; Westenbroek and others, 2010). However, for this study, the preferred approach is to build on previous water-budget models developed by USGS for the State of Hawai‘i because (1) these models are better adapted to conditions unique to O‘ahu, such as a persistent fog and cloud cover for many locations and a pronounced orographic influence on climate, and (2) a high degree of spatial detail is needed for defining the model subareas. The high degree of spatial detail allows the model to represent the wide range of climate conditions, vegetation, soils, and land uses on O‘ahu.

Conceptual Model

The water-budget model used here to estimate groundwater recharge is a “threshold-type” or “reservoir” model utilizing a variation of the Thornthwaite and Mather (1955) mass-balance procedure. The two generalized flow diagrams of the water-budget model—one for nonforest land covers and one for forest land covers are shown in figure 5. The plant-root zone reservoir is included in the model for nonforest and forest land covers. The forest-canopy reservoir is included in the model for forest land covers only.

The volume of the plant-root zone reservoir is based on the estimated root depth of different plant types and the available water capacity of different soil types. Water entering, leaving, and being stored within the plant-root zone reservoir is accounted for using a daily computational interval. At the end of a day, if the volume of water entering the system exceeds the storage capacity of the plant-root zone reservoir, given the antecedent water content and water losses from ET, the reservoir overflows. This overflow is counted as groundwater recharge by the model. In some areas, recharge includes direct recharge from reservoir and cesspool seepage. All water infiltrating the substrate beneath the plant-root zone reservoir as overflow or direct recharge is considered recharge.

Direct runoff is the fraction of precipitation (rainfall and fog interception) that does not contribute to net moisture gain within the plant-root zone reservoir. Direct runoff excludes base flow, which is groundwater discharge to streams. Direct runoff is assumed to either be diverted to other areas or ultimately discharged to the ocean. Re-infiltration of direct runoff is not quantified in the model, although it is indirectly accounted for in the empirical functions used to calculate direct runoff.

Unlike the plant-root zone reservoir, precipitation is not allowed to be stored in the forest-canopy reservoir for more than a day. For each daily computational period, precipitation in the forest-canopy reservoir either evaporates as canopy evaporation or reaches the soil as part of net precipitation. Net precipitation is calculated as the sum of fog interception and rainfall minus canopy evaporation, and thus represents outflow from the forest-canopy reservoir. Net precipitation is partitioned into direct runoff and inflow to the plant-root zone. The plant-root zone reservoir and the forest-canopy reservoir are herein referred to as the plant-root zone and the forest canopy, respectively.

Model Calculations

Groundwater recharge for the Island of O‘ahu is calculated using the water-budget model and input data that quantify the spatial and temporal distributions of rainfall, fog interception, irrigation, ET, direct runoff, soil type, land cover, and seepage from reservoirs and septic systems. For the model calculations, the Island of O‘ahu is subdivided into small areas with homogeneous properties, termed subareas. A map of subareas is generated using Esri ArcGIS software (*www.esri.com*) by intersecting (merging) spatial datasets that characterize the spatial distribution of rainfall, fog, irrigation, reference ET, runoff, soil type, and land cover. Intersecting the spatial datasets resulted in 387,533 subareas—with an average area of about 1.0 acres—for the O‘ahu water-budget model.

Each subarea is treated independently by the water-budget model. Water transfers between subareas are not included in the model calculations. The model domain of each subarea extends vertically from the vegetation canopy to the base of the plant-root zone, the part of the soil and bedrock containing roots. Properties of the substrate beneath the plant-root zone are not included in the model calculations.

For each subarea, the water-budget model calculates recharge on a daily basis for the period of the scenario. This study considers two scenarios, one for average climate conditions and one for drought conditions. Mean annual recharge for each scenario is determined for each subarea. Mean annual recharge for subareas is also summed over larger areas of interest, including O‘ahu’s 23 aquifer systems.

For each subarea, the model calculates an interim moisture storage at the start of each day. Interim moisture storage is the amount of water that enters the plant-root zone for the current day plus the amount of water already in the plant-root zone from the previous day. For the first day of the simulation, a value for the amount of water already in the plant-root zone from the previous day (initial soil moisture) must be assigned. For subareas with nonforest land covers, interim moisture storage, X_i, is given by the equation

$$X_i = R_i + F_i - U_i + I_i + L_i + W_i + M_{i-1}, \qquad (1a)$$

where

X_i = interim moisture storage for current day [L],
R_i = rainfall for current day [L],
F_i = fog interception for current day [L],
U_i = direct runoff for current day [L],
I_i = irrigation for current day [L],
L_i = septic-system leachate for current day [L],
W_i = excess water from the impervious fraction of the subarea distributed over the pervious fraction of the subarea [L],
M_{i-1} = moisture storage at the end of the previous day (i-1) [L], and
i = subscript designating current day.

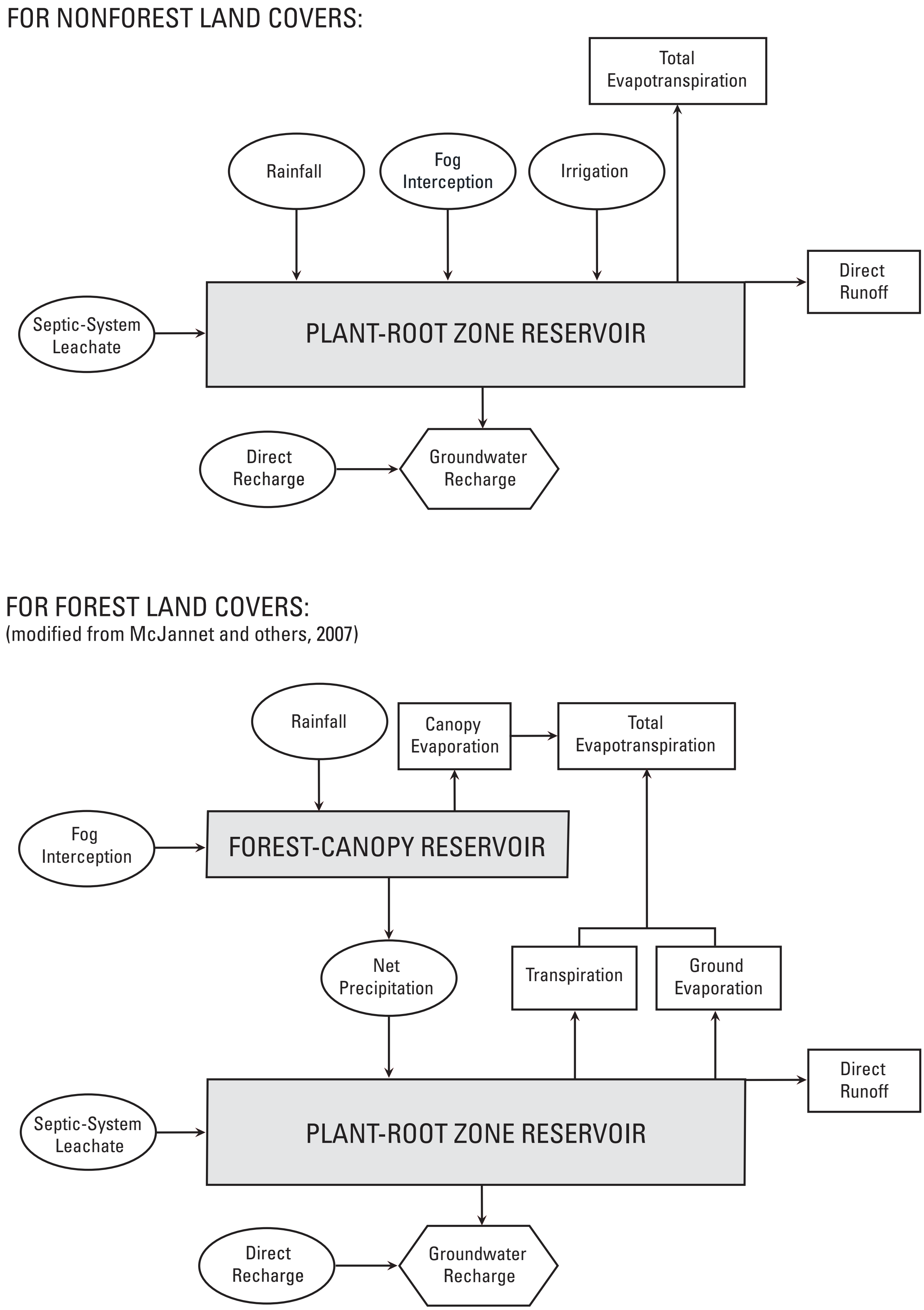

Figure 5. Generalized water-budget flow diagrams for nonforest and forest land covers.

For subareas with forest land covers, interim moisture storage is given by the equation

$$X_i = (NP)_i - U_i + L_i + W_i + M_{i-1}, \quad \text{(1b)}$$

where

$(NP)_i$ = net precipitation for current day [L].

For subareas with forest land covers, net precipitation is calculated as precipitation minus canopy evaporation, which is the amount of precipitation that is intercepted by and evaporates from the leaves, stems, and trunks of a forest. Precipitation is the sum of rainfall and fog interception:

$$P_i = R_i + F_i \quad \text{(2)}$$

where

P_i = precipitation for current day [L].

Net precipitation is calculated as:

$$(NP)_i = P_i - (CE)_i, \quad \text{(3)}$$

where

$(CE)_i$ = forest-canopy evaporation for current day [L].

Forest-canopy evaporation is calculated in the water-budget model using an approach that is derived from the rainfall-interception model described by Gash and others (1995), herein referred to as the Gash model. Using this approach, canopy evaporation for a given day and location depends on precipitation amount, forest structure, and mean rates of evaporation and precipitation. The Gash model was modified for this study so that (1) precipitation includes rainfall and fog interception, instead of rain only, and (2) water cannot be stored on the forest canopy for more than a day. The forest structure is characterized in terms of canopy cover, canopy capacity, trunk-storage capacity, and the proportion of precipitation diverted to stemflow. Canopy cover, c, is the fraction of a forested subarea that is covered by leaves, stems, and branches of trees. Canopy capacity, S, is the depth of water left on the canopy when rainfall and throughfall have ceased (Gash and Morton, 1978). Evaporation of water from tree trunks is accounted for using the proportion of precipitation that is diverted to stemflow, p, and trunk-storage capacity, k, which is considered in terms of an equivalent depth of precipitation. The last parameter needed for the Gash model is the ratio of the mean evaporation rate to the mean precipitation rate during saturated conditions, V.

To calculate forest-canopy evaporation, the first step is to determine the minimum depth of precipitation necessary to saturate the forest canopy, P' (Gash and others, 1995). On the basis of equation 2 in Gash and others (1995), P' for subareas with forest land covers is calculated as

$$P' = -\{S \div (c \times V)\} \times \ln(1 - V). \quad \text{(4)}$$

where

P' = precipitation necessary to saturate the canopy [L],
S = canopy capacity per unit of ground area [L] (a constant),
c = canopy cover per unit of ground area [dimensionless], and
V = ratio of mean evaporation rate to mean precipitation rate during saturated conditions [dimensionless].

On the basis of the revised analytical form of the Gash model presented in table 1 of Gash and others (1995), forest-canopy evaporation for a given day, $(CE)_i$, is calculated for three canopy conditions as follows:

for $P_i < P'$,

$$(CE)_i = c \times P_i,$$

for $P_i \geq P'$ and $P_i \leq k \div p$,

$$(CE)_i = c \times P' + c \times V \times (P_i - P') + p \times P_i,$$

for $P_i \geq P'$ and $P_i > k \div p$,

$$(CE)_i = c \times P' + c \times V \times (P_i - P') + k, \quad \text{(5)}$$

where

k = trunk-storage capacity [L] (a constant), and
p = proportion of precipitation diverted to stemflow [dimensionless].

For each subarea with impervious surfaces, such as paved roads and buildings, the interim moisture-storage equations include the factor W_i (see equations 1a and 1b), which is a function of the fraction of the subarea that is impervious. For subareas with no impervious surfaces, W_i is zero. The fraction of the subarea that is impervious, z, is used to separate, from the total rain that falls in a subarea, a depth of water that is treated computationally as though it fell on an impervious surface. Based on the rainfall-retention capacity of the impervious surface, some water is subtracted to account for direct evaporation. The remaining water is considered excess water, W_i. For subareas without storm-drain systems, W_i is added to the water budget of the pervious fraction of the model subarea. In this case, the total daily water input for the pervious fraction of a subarea includes excess water from the impervious fraction (equations 1a and 1b). For subareas with storm-drain systems, W_i is assumed to be collected by storm-drain systems and is added to runoff or to direct recharge, depending on location.

For subareas with impervious surfaces, excess water, W_i, is determined using the following conditions:

$$X1_i = P_i - U_i + T_{i-1}, \tag{6}$$

for $X1_i \leq N$,

$$W_i = 0, \text{ and } X2_i = X1_i,$$

for $X1_i > N$,

$$W_i = (X1_i - N) \times z \div (1 - z), \text{ and } X2_i = N, \tag{7}$$

where

$X1_i$ = first interim moisture storage on the surface of impervious area for current day [L],
$X2_i$ = second interim moisture storage on the surface of impervious area for current day [L],
T_{i-1} = water storage (ponded water) on the surface of impervious area at the end of the previous day (i –1) [L],
N = rainfall-retention capacity of the impervious surface (maximum amount of water storage on the surface of impervious area) [L], and
z = fraction of area that is impervious [dimensionless].

The water storage on the surface of the impervious area at the end of the current day, T_i, is determined from the equation:

for $X2_i \leq G_i$,

$$T_i = 0,$$

for $X2_i > G_i$,

$$T_i = X2_i - G_i, \tag{8}$$

where

G_i = reference ET for current day [L], and
T_i = water storage (ponded water) on the surface of impervious area at the end of day [L].

The next step in the water-budget computation is to determine the amount of water that will be removed from the plant-root zone by ET. Actual ET is a function of potential ET and interim moisture, X_i. The plant-root zone loses water to the atmosphere at the potential-ET rate if sufficient water is available. At all sites, potential ET, $(PE)_i$, is calculated as the product of (1) reference ET, G_i, the potential ET of a grass reference surface, and (2) crop coefficient, k_c, a factor that depends on vegetation and land cover.

$$(PE)_i = k_c \times G_i \tag{9}$$

where

$(PE)_i$ = potential-ET rate for the current day [L/T], and
k_c = crop coefficient of land cover [dimensionless].

For moisture storage greater than or equal to a threshold value, C_i, the actual-ET rate is assumed to be equal to the potential-ET rate. For moisture storage less than C_i, the actual-ET rate is assumed to occur at a reduced rate that declines linearly with soil-moisture content:

for $M \geq C_i$,

$$E = (PE)_i, \text{ and}$$

for $M < C_i$ and $C_i > 0$

$$E = M \times (PE)_i \div C_i, \tag{10}$$

where

E = instantaneous actual-ET rate [L/T],
M = instantaneous moisture storage [L], and
C_i = threshold moisture storage for the current day below which the actual-ET rate is less than the potential-ET rate [L].

The threshold moisture storage, C_i, is estimated using the model of Allen and others (1998) for soil moisture. In this model, a depletion fraction, d, which ranges from 0 to 1, is defined as the fraction of maximum moisture storage that can be depleted from the plant-root zone before moisture stress causes a reduction in the actual-ET rate. Values for d are assigned to land-cover classes on the basis of data in Allen and others (1998). The threshold moisture, C_i, is estimated from d by the equation

$$C_i = (1 - d) \times M_m, \tag{11}$$

where

M_m = moisture-storage capacity of the plant-root zone [L], and
d = depletion fraction [dimensionless].

The moisture-storage capacity of the plant-root zone, M_m, expressed as a depth of water, is equal to the plant-root depth, D, multiplied by the available water capacity of the soil, ϕ. Available water capacity is the difference between the volumetric field-capacity moisture content and the volumetric wilting-point moisture content:

$$M_m = D \times \phi, \tag{12}$$

where

D = plant-root depth [L],
ϕ = available water capacity, $\theta_{fc} - \theta_{wp}$ [L^3/L^3],
θ_{fc} = volumetric field-capacity moisture content [L^3/L^3], and
θ_{wp} = volumetric wilting-point moisture content [L^3/L^3].

In the water-budget model, the actual-ET rate from the plant-root zone may be (1) equal to the potential-ET rate for part of the day and less than the potential-ET rate for the remainder of the day, (2) equal to the potential-ET rate for the entire day, or (3) less than the potential-ET rate for the entire day. The total ET from the plant-root zone during a day is a function of the potential-ET rate, $(PE)_i$, interim moisture storage, X_i, and the threshold moisture content, C_i. By recognizing that $E = -dM/dt$, the total depth of water removed by ET from the plant-root zone during a day, E_i, is determined as follows:

for $X_i > C_i$ and $C_i > 0$,

$$E_i = (PE)_i t_i + C_i\{1 - \exp[-(PE)_i(1-t_i) \div C_i]\},$$

for $X_i > C_i$ and $C_i = 0$,

$$E_i = (PE)_i t_i,$$

for $X_i \le C_i$ and $C_i > 0$,

$$E_i = X_i\{1 - \exp[-(PE)_i \div C_i]\}, \text{ and}$$

for $X_i = C_i$, and $C_i = 0$,

$$E_i = 0, \tag{13}$$

where

E_i = evapotranspiration from the plant-root zone during the day [L],
t_i = time during which moisture storage is above C_i [T]. It ranges from 0 to 1 day and is calculated as follows:

for $(X_i - C_i) < (PE)_i(1 \text{ day})$

$$t_i = (X_i - C_i) \div (PE)_i, \text{ and}$$

for $(X_i - C_i) \ge (PE)_i(1 \text{ day})$,

$$t_i = 1. \tag{14}$$

After accounting for runoff (equation 1a or 1b), actual ET from the plant-root zone for a given day is subtracted from the interim moisture storage, and any moisture remaining above the maximum moisture storage is assumed to be recharge. The daily rate of direct recharge from anthropogenic sources, including seepage from cesspools and reservoirs, is also added to daily recharge at this point. Recharge and moisture storage at the end of a given day are assigned according to the following conditions:

for $X_i - E_i \le M_m$,

$$Q_i = DR, \text{ and } M_i = X_i - E_i, \text{ and}$$

for $X_i - E_i > M_m$,

$$Q_i = (X_i - E_i - M_m) + DR, \text{ and } M_i = M_m, \tag{15}$$

where

Q_i = groundwater recharge during the day [L], and
M_i = moisture storage at the end of the current day (i) [L], and
DR = daily rate of direct recharge [L].

Iteration

To mitigate possible effects of arbitrary starting values and random selection of monthly rainfall fragment sets (see Rainfall section, below), the recharge model was run multiple times and the results were averaged. To determine the appropriate number of simulations to run, the recharge model for was run 50 times and the absolute percentage change in cumulative mean recharge for the island was calculated for each successive simulation (fig. 6). The average percentage change did not exceed 0.002 percent after 25 simulations. This very small value, 0.002 percent, was determined to be adequate for this study. Accordingly, for each model scenario, the recharge model was run 25 times and the results were averaged

Model Input

Land Cover

A land-cover map for Oʻahu representative of 2010 conditions, herein referred to as the 2010 land-cover map, was developed for this study. The 2010 land-cover map identifies 18 types of land cover (fig. 4) and was merged with other spatial datasets when creating the map of subareas for the water-budget model. The 2010 land-cover map was used in the computation of recharge for both scenarios of this study: average climate conditions and drought conditions. The 2010 land-cover map was created by modifying the LANDFIRE Existing Vegetation Type map for Oʻahu (U.S. Geological Survey, 2010), herein referred to as the Landfire map. Modifications to the Landfire map included converting

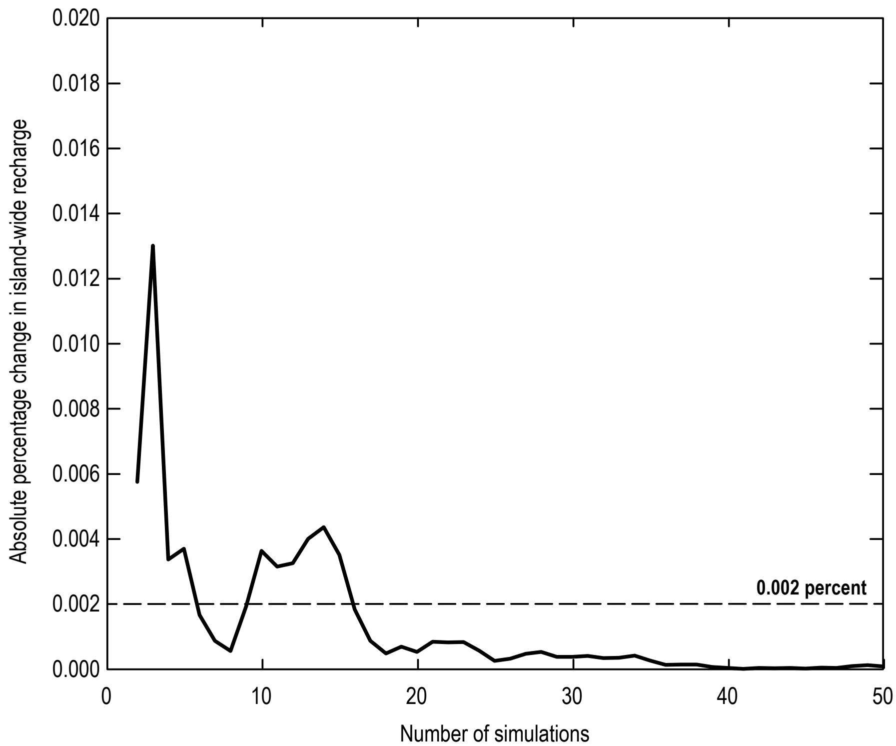

Figure 6. The average incremental percentage change in recharge for water-budget subareas with each successive model simulation.

it from a raster dataset to a vector dataset, combining similar land-cover classes, and adding boundaries of golf courses and selected crops. These modifications were done using Esri ArcGIS software, as summarized in the following paragraphs.

Some land-cover groups of the Landfire map were combined into more general classes for the 2010 land-cover map. Landfire groups Hawaiian Dry Grassland, Hawaiian Mesic Grassland, and Introduced Perennial Grassland and Forbland were combined into Grassland for the 2010 land-cover map (fig. 4). Landfire groups Hawaiian Dry Shrubland, Hawaiian Mesic Shrubland, and Introduced Upland Vegetation–Shrub were combined into Shrubland. Landfire groups Hawaiian Dry Forest, Hawaiian Mesic Forest, and Hawaiian Rainforest were combined into Native forest. The Landfire group Introduced Upland Vegetation-Treed was renamed Alien forest.

Locations of golf courses and selected crops not specified in the Landfire map were delineated in the 2010 land-cover map to improve estimates of irrigation, ET, and recharge for parcels with these types of land cover. The boundaries of golf courses, coffee, pineapple, and taro in the 2010 land-cover map (fig. 4) were defined using sources other than the Landfire map. The boundaries of golf courses and fields of corn, coffee, and pineapple were digitized using 2010–13 satellite imagery in Google Earth (*earth.google.com*). Fields of taro were digitized on the basis of those identified in Gingerich and others (2007). All other parcels classified as agriculture in the Landfire map that appeared in the imagery as being actively cultivated were classified as diversified agriculture. Agriculture parcels that appeared in the imagery as uncultivated and mostly covered by grass were defined as grassland.

Impervious surfaces include paved surfaces and buildings. Excess water from the impervious fraction of a subarea, W_i, that is distributed to the pervious fraction of the subarea depends on the impervious fraction of the subarea, z. The impervious fraction of each subarea was calculated from a map of impervious surfaces on O‘ahu (National Oceanic and Atmospheric Administration, 2008).

Rainfall

Monthly Rainfall

Gridded maps of rainfall for each of the 360 months during 1978–2007 for the Island of O‘ahu were used to define the spatial and temporal distribution of rainfall in the water-budget calculations. These maps are a subset of the 1,056 rainfall maps that were generated for the Rainfall Atlas of Hawai‘i (Giambelluca and others, 2013) for each month from 1920–2007 for the Hawaiian Islands by Frazier and others (2016). The monthly rainfall maps for 1978–2007 were used in the water budget because they have the same base period as the mean monthly and mean annual rainfall datasets in Giambelluca and others (2013). Rainfall maps are formatted 8.1-arcsecond grids, where each grid cell is about 14 acres (770 by 820 ft) and has an estimated rainfall value for each month during 1978–2007. Using Esri ArcGIS software, the monthly rainfall maps were converted from a raster grid to polygon format for use in the water-budget model. The rainfall polygons were intersected with the other spatial datasets when creating the map of subareas for the water-budget model.

Cell-by-cell comparisons of the mean monthly rainfall calculated for 1978–2007 from the Frazier and others (2016) dataset and the mean monthly values in Giambelluca and others (2013) showed differences. For consistency, the monthly rainfall values from Frazier and others (2016) were adjusted to produce the same mean monthly rainfall values for 1978–2007 as Giambelluca and others (2013). A total of 12 monthly adjustment factors for each grid cell were determined as the ratio of the 1978–2007 mean monthly rainfall from Giambelluca and others (2013) to the 1978–2007 mean monthly rainfall calculated from Frazier and others (2016). In this study, the monthly rainfall for each grid cell was determined by multiplying the value in Frazier and others (2016) by the appropriate monthly adjustment factor.

Daily Rainfall

Estimates of the actual rainfall distribution on Oʻahu for each day during 1978–2007 were not available and were not developed as part of this study. Although records of daily rainfall measurements at gages were available, reconstructing the actual daily rainfall pattern was not attempted because (1) records for many gages have considerable gaps, (2) the spatial interpolation of daily records for gages would have high uncertainty, and (3) the monthly rainfall maps of Frazier and others (2016) were considered to be the best dataset available for estimating historical rainfall patterns.

For input to the water-budget model, daily rainfall was synthesized by disaggregating the monthly values of the 1978–2007 rainfall distribution maps using the method of fragments (for example, Oki, 2002). The method of fragments creates a synthetic sequence of daily rainfall from monthly rainfall by imposing the rainfall pattern from a rain gage with daily data. The synthesized daily rainfall data approximate the long-term average character of daily rainfall, such as frequency, duration, and intensity, but may not reproduce the historical daily rainfall record during 1978–2007.

Daily rainfall measurements at 47 rain gages on Oʻahu during 1905–2011 were used to disaggregate monthly rainfall into daily rainfall for the water-budget model. Rain gages were selected on the basis of location, and the length and completeness of daily records. Daily rainfall data for the period of record of each rain gage were obtained from the National Climatic Data Center (www.ncdc.noaa.gov) and the USGS (http://waterdata.usgs.gov/hi/nwis/nwis). Thiessen polygons were drawn around each of the rain gages, and the daily rainfall pattern within each Thiessen polygon was assumed to be the same as the pattern at the rain gage within the Thiessen polygon (fig. 3).

For each rain gage, daily rainfall fragments were calculated by dividing each daily rainfall measurement for a particular month by the total rainfall measured at the gage for that month. This resulted in a set of fragments for that particular month in which the total number of fragments was equal to the number of days in the month. Fragment sets were compiled for every gage for every month in which complete daily rainfall measurements were available. Fragment sets were grouped by month of the year and by rain gage.

In the water-budget calculation, the fragment set used for a given gage for a given month was selected randomly from among all available sets for that gage for that month. Daily rainfall for a given month was synthesized by multiplying total rainfall for that month (from the monthly rainfall maps) by each fragment in the set, thereby providing daily rainfall, R_i, for equation 1a or 1b.

Fog Interception

Fog is often persistent on the mid-elevation mountain slopes of most Hawaiian islands, occurring during periods of onshore, upsloping winds favorable for orographic cloud formation. Fog may be persistent at elevations as low as about 2,000 to 3,000 ft (Juvik and Ekern, 1978). Orographic cloud formation is often limited or capped by the base of the trade-wind inversion, which commonly occurs between 5,000 and 10,000 ft (Giambelluca and Schroeder, 1998). This limitation on cloud formation hinders the growth of large raindrops and produces high ratios of fog to rain near or at the inversion-base elevation (Juvik and Ekern, 1978). Above the base of the inversion, fog tends to dissipate quickly in the drier air regime.

Where fog is persistent, the interception of this moisture by vegetation has been shown to be a significant component of the water budget (Ekern, 1964; Juvik and Ekern, 1978; Juvik and others, 1993; 2011; Juvik and Nullet, 1995; Scholl and others, 2007). Fog interception occurs through the processes of turbulent diffusion and gravitational sedimentation of droplets onto vegetative surfaces, mainly leaves or needles (Bruijnzeel and others, 2005). Rates of fog interception are highly site dependent and influenced by both meteorological and biotic variables including (1) the duration and frequency of fog periods, (2) wind speed and direction, (3) liquid water content of fog, and (4) structural characteristics of the forest, such as height, size, spatial pattern, and the physical characteristics of leaves and epiphytes (Walmsley and others, 1996; Bruijnzeel and others, 2005; Villegas and others, 2007). The quantification of fog interception is a complex endeavor and is the subject of continuing research, both in Hawaiʻi and worldwide.

For leeward areas above 2,000 ft on Oʻahu, estimates of fog interception for this study are based on fog-interception data collected in the Koʻolau Range. Monthly ratios of fog-interception to rainfall (table 3) were calculated from data presented in Ekern (1983). For leeward areas, the lowest ratio, 0.01, occurs in October, and the highest ratio, 0.15, occurs in February. For windward Oʻahu above 2,000 ft, a relatively small area where no fog studies have been conducted, a ratio of 0.20 was used for all months. This is the same fog-interception to rainfall ratio used in Engott and Vana (2007) for the windward West Maui Mountains.

Fog interception is primarily a phenomenon associated with trees and other tall vegetation because the magnitude of fog interception is directly related to the height of the vegetated surface (Walmsley and others, 1996; Bruijnzeel and others, 2005).

Table 3. Ratios of fog interception to rainfall used in the water-budget model for the Island of Oʻahu, Hawaiʻi.

Month	Aspect	
	Leeward	Windward
January	0.12	0.20
February	0.15	0.20
March	0.08	0.20
April	0.08	0.20
May	0.02	0.20
June	0.12	0.20
July	0.09	0.20
August	0.06	0.20
September	0.05	0.20
October	0.01	0.20
November	0.05	0.20
December	0.11	0.20

Accordingly, fog interception for nonforest land covers is assumed to be negligible, except for shrubland, which is assumed to intercept fog at one-half the rate of forest land covers.

Irrigation

Irrigation was applied to golf courses and five agricultural land covers: corn, coffee, pineapple, diversified agriculture, and taro (fig. 4). Irrigation was also applied to medium- and high-intensity developed subareas in order to simulate the watering of urban landscapes. Irrigation rates were estimated using a demand-based approach. Irrigation demand for a given subarea is estimated on the basis of monthly rainfall, runoff, potential evapotranspiration, and irrigation-method efficiency:

for $(PE)_m + U_m > R_m$,

$$I_m = [(PE)_m + U_m - R_m] / g$$

for $(PE)_m + U_m \leq R_m$,

$$I_m = 0 \tag{16}$$

where

$(PE)_m$ = potential evapotranspiration for month m [L] (varies by location),
U_m = amount of runoff for month m [L],
R_m = amount of rainfall for month m [L],
I_m = amount of irrigation for month m [L], and
g = irrigation-method efficiency [dimensionless].

Irrigation-method efficiency is the fraction of applied irrigation water that becomes available for plant consumption. Corn, diversified agriculture, and pineapple were assumed to use drip irrigation, which has an irrigation-method efficiency of 0.85 (University of Hawaiʻi, 2008). Coffee was assumed to use micro-spray irrigation, which has an irrigation efficiency of 0.80 (University of Hawaiʻi, 2008). Golf courses and medium- and high-intensity developed land covers were assumed to use sprinkler irrigation, which has an irrigation efficiency of 0.70 (University of Hawaiʻi, 2008).

For all irrigated land covers other than pineapple, monthly irrigation calculated using equation 16 was allocated in equal amounts for each day of a given month. Similar to the approach taken in Engott and Vana (2007) for pineapple irrigation, the monthly irrigation volume calculated for pineapple using equation 16 was uniformly distributed on days 1, 2, 3, 8, 9, 10, 15, 16, 17, 22, 23, 24, and 28 of each month. Simulation of the pineapple cultivation cycle was not attempted in this study. Corn irrigation for this study is based on a cultivation cycle of 2 crops per year. Only 25 percent of the corn land cover is cultivated at any one time, leaving the remaining 75 percent fallow/grassland. This approach was developed on the basis of cultivation practices on Molokaʻi.

An irrigation-estimation multiplier was used to adjust the irrigation estimate (equation 16) for the diversified agriculture land-cover category because of its relatively large total area (fig. 4) combined with the large uncertainty involved in selecting crop parameters, given the wide variety of crops represented by this category. An irrigation-estimation multiplier of 0.55 was used on the basis of irrigation-supply information for fields served by the Waiāhole Ditch in central and southern Oʻahu. An irrigation-estimation multiplier also was used for the medium- and high-intensity land-cover categories to calibrate the irrigation estimates from equation 16 to the rates used in Giambelluca (1983) and Giambelluca and others (2014) for urban irrigation in southern Oʻahu.

Owing to the nature of wetland taro cultivation, the irrigation rate for taro was not calculated using the demand-based approach described above. Instead, the irrigation rate for taro, which is grown in flooded ponds, was set equal to a constant recharge rate over the area of active taro cultivation. A constant recharge rate of 455 in/yr was used, which is the average of the recharge rates derived from four water-use studies for various taro fields in Hawaiʻi (Miles, 1931; Watson, 1964; La Pena and Melchor, 1984; Berg and others, 1997).

Septic-System Leaching

Some areas on Oʻahu have on-site systems to dispose of wastewater. Whittier and El-Kadi (2009) compiled an inventory of on-site wastewater-disposal systems on Oʻahu. For each tax map key (TMK) parcel, Whittier and El-Kadi (2009) specify the number and type (class) of on-site disposal systems and the total estimated wastewater effluent flux. For the water-budget calculation, all effluent flux for each TMK parcel was applied daily as a uniform depth over the parcel's area. Each TMK parcel may contain one or more subareas. Hence, all subareas within a TMK parcel that contains at least one on-site disposal system can have septic effluent, including subareas with undeveloped land covers. For TMK parcels with cesspools, the effluent flux was considered direct recharge (fig. 5). For TMK parcels with other types of septic-systems, the effluent flux was added to the plant-root zone as septic-system leachate (fig. 5).

Storm-Drain Systems

Some developed areas on Oʻahu have storm-drain systems that collect and divert rainwater. Water collected by storm-drain systems may be diverted into streams, gulches, the ocean, infiltration basins, and drywells, thereby affecting the water budget. For this study, subareas with medium- and high-intensity developed land covers in (1) the Waiʻanae, Central, Pearl Harbor, and Honolulu aquifer sectors and (2) the Koʻolaupoko and Waimānalo aquifer systems were assumed to have storm-drain systems (figs. 1 and 4). For these subareas, excess water, W_i, that flows off the impervious fraction of a subarea was assumed to be collected by a storm-drain system instead of flowing to the pervious fraction of the subarea (see equation 7). This collected water was assumed to not contribute to recharge.

Direct Runoff

Direct runoff is the fraction of rainfall that does not contribute to net moisture gain within the plant-root zone (fig. 5). Direct runoff of rainfall consists of overland flow and subsurface storm flow that rapidly returns infiltrated water to the stream (Oki, 2003). In the water-budget calculation, direct runoff was estimated as a fraction of rainfall using runoff-to-rainfall ratios. This approach was also used in previous water-budget studies for Hawaiʻi and other Pacific islands (for example, Izuka and others, 2005; Engott and Vana, 2007; Engott, 2011; Gingerich and Engott, 2012; Johnson, 2012) and was shown to provide reasonable estimates of regional average direct runoff using a minimal level of complexity.

The spatial variability of runoff-to-rainfall ratios depends on numerous factors including geology, climate, soil type, topography, and land use. Runoff-to-rainfall ratios are expected to be highest where the rainfall amount and intensity are high, permeability of the soils and substrate is low, slopes are steep, and soil moisture is high (Oki, 2003). The temporal variability in runoff-to-rainfall ratios reflects event characteristics, such as antecedent soil moisture and rainfall intensity. In Hawaiʻi, runoff-to-rainfall ratios generally follow a seasonal pattern. Runoff-to-rainfall ratios are highest during the wet-season months and lowest during the dry-season months.

In the water-budget model, daily direct runoff, U_i, was calculated by multiplying daily rainfall, R_i, with seasonal (wet and dry season) runoff-to-rainfall ratios assigned to catchment zones. Catchment zones were delineated by Rea and Skinner (2012) for a stream network developed using a 10-m digital elevation model with a flow-accumulation threshold of 20,000 cells. For this study, each catchment zone was assigned two attributes: (1) gaged or ungaged, and (2) windward or leeward (fig. 7). The boundaries of the drainage basins of selected stream-gaging stations are from Rosa and Oki (2010), and the boundary between windward and leeward regions is based on topographic divides and consistent with previous studies (Yamanaga, 1972; Oki and others, 2010). The runoff-to-rainfall ratio assigned to each catchment zone and used to calculate direct runoff was selected as one of the following (1) the observed seasonal runoff-to-rainfall ratio for the season, year, and location of interest, if available, (2) the observed mean seasonal runoff-to-rainfall ratio for the location of interest, or (3) the mean seasonal runoff-to-rainfall ratio estimated using a regression equation for the location of interest. A description of the approach used to calculate the ratios is presented below. For this study, November through April was considered the wet season; May through October was considered the dry season.

Seasonal runoff-to-rainfall ratios assigned to catchment zones in the water-budget model were calculated from data for drainage basins of stream-gaging stations. These drainage basins consist of one or more catchment zones. For gaged drainage basins consisting of a single catchment zone, observed seasonal or mean seasonal runoff-to-rainfall ratios for the gaged basin were assigned to the catchment zone. For gaged drainage basins consisting of multiple catchment zones, observed seasonal or mean seasonal runoff-to-rainfall ratios for the gaged drainage basin were spatially disaggregated to each catchment zone within the gaged basin. Catchment zones in ungaged areas were assigned mean seasonal runoff-to-rainfall ratios derived from regional-regression models.

Computation of Seasonal Runoff-to-Rainfall Ratios

Runoff and rainfall data for drainage basins of 55 stream-gaging stations (25 on Maui, 13 on Kauaʻi, and 17 on Oʻahu) were used to derive seasonal runoff-to-rainfall ratios for the water-budget model (table 4). Data for stations on Maui and Kauaʻi were included in the analysis to derive broadly applicable empirical models for estimating direct runoff in ungaged areas. Stream-gaging stations selected for the runoff analysis had (1) at least eight complete years of daily mean discharge records between 1920 and 2007, (2) a drainage-basin area greater than 0.2 mi^2, and (3) unregulated streamflow or regulated streamflow with complete and reliable records of daily mean diverted flow available to reconstruct total streamflow at the gage. For drainage basins with more than one stream-gaging station, only the station at the lowest elevation was used in the runoff analysis because it had the largest drainage basin. Additionally, concurrent streamflow data for two stations within a drainage basin was generally absent or insufficient for improving direct runoff estimates.

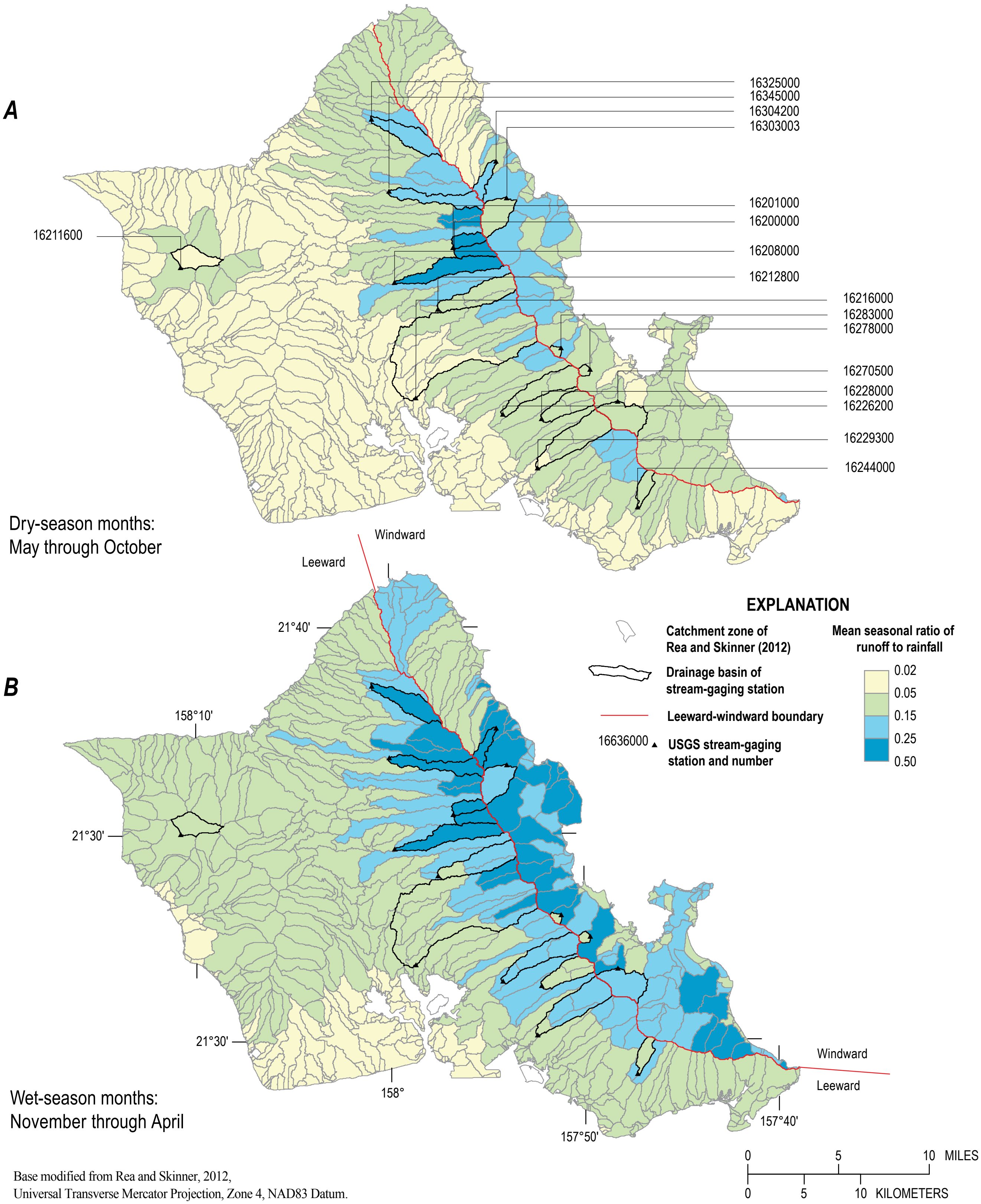

Figure 7. Mean runoff-to-rainfall ratios for the (*A*) dry-season months (May through October) and (*B*) wet-season months (November through April) for drainage basins of selected stream-gaging stations and catchment zones on the Island of O‘ahu, Hawai‘i (modified from Rea and Skinner, 2012).

The drainage basins of the selected stream-gaging stations were delineated using the USGS StreamStats application for Hawaiʻi (Rosa and Oki, 2010). Rainfall within each drainage basin was calculated using gridded maps of monthly rainfall (Frazier and others, 2016).

Because streamflow measured at most gaging stations consists of direct runoff and base flow, the base-flow component was estimated and subtracted from the total streamflow. Streamflow at stations 16500100 and 16660000 on Maui and station 16013000 on Kauaʻi was ephemeral and was assumed to have no base flow. Base flow at the other gaged basins was estimated using a computerized base-flow separation method (Wahl and Wahl, 1995). This method has been used in numerous other studies in Hawaiʻi (for example, Izuka and others, 2005; Engott and Vana, 2007; Engott, 2011) and provides a reasonable estimate of base flow for perennial streams in Hawaiʻi. The method defines local streamflow minimums within consecutive, nonoverlapping n-day periods and requires two parameters (1) f, the turning-point test factor, and (2) n, the number of days in a test window. In this study, the f value used for all stations was 0.9. The n values were determined for each station using the method described by Wahl and Wahl (1995) and ranged from three to five days (table 4). Daily base flow was subtracted from daily streamflow to determine daily direct runoff.

Observed seasonal runoff-to-rainfall ratios were calculated for 17 gaged drainage basins on Oʻahu that were operational during 1978–2007. These observed ratios are not presented in this report. Each observed seasonal runoff-to-rainfall ratio for the gaged drainage basins was calculated as the quotient of cumulative direct runoff and cumulative rainfall during the season. For example, the observed runoff-to-rainfall ratio for a gaged basin during the dry season of 2001 was calculated as the quotient of cumulative direct runoff and cumulative rainfall during May–October 2001.

For each of the 55 selected gaged drainage basins on Kauaʻi, Oʻahu, and Maui, mean seasonal runoff-to-rainfall ratios were calculated for a period with rainfall and runoff conditions generally representative of those during 1978–2007 (table 4). Each mean seasonal runoff-to-rainfall ratio for the gaged drainage basins was calculated as the quotient of cumulative direct runoff and cumulative rainfall during the appropriate season of the selected period. For example, the mean dry season runoff-to-rainfall ratio for stream-gaging station 16228000 was calculated as the quotient of cumulative direct runoff and cumulative rainfall during May–October between 1949 and 1978.

Criteria for selecting periods of record were determined by examining temporal variations in seasonal runoff-to-rainfall ratios for stream-gaging stations that were operational during 1978–2007. For these stations, mean seasonal runoff-to-rainfall ratios calculated for 1978–2007 were compared with those calculated for smaller, subset periods during 1920–2007. The results of these comparisons show that the difference between mean seasonal runoff-to-rainfall ratios calculated for 1978–2007 and those calculated for subset periods decreases with increasing record length of the subset period and with decreasing differences between mean annual rainfall during 1978–2007 and that of the subset period. Accordingly, the period of record selected to calculate mean seasonal runoff-to-rainfall ratios was (1) the entire period during 1978–2007 for stream-gaging stations with at least 24 complete years of record during 1978–2007, (2) the longest contiguous period during 1920–2007 that had less than 5-percent difference in mean annual rainfall, relative to rainfall for 1978–2007, for all remaining stream-gaging stations on perennial streams with base flow, and (3) the entire period of record for three stream-gaging stations on ephemeral streams. Despite the relatively high rainfall during their periods of record (table 4), the latter three stations were included in the analysis owing to the sparseness of runoff data for areas in the Hawaiian Islands with ephemeral streams.

Runoff-to-Rainfall Ratios Assigned to Ungaged Catchment Zones

Ungaged catchment zones are outside of the drainage basins of the 17 selected stream-gaging stations on Oʻahu (fig. 6). Direct runoff for ungaged catchment zones was calculated using mean seasonal runoff-to-rainfall ratios derived from the four regional-regression equations in table 5. Separate windward and leeward regression equations were derived for the wet and dry seasons. The regional-regression equations relate mean seasonal runoff-to-rainfall ratios and basin characteristics and were developed with methods consistent with discussion given in Helsel and Hirsch (1992).

The regional-regression equations were derived from mean seasonal runoff-to-rainfall ratios and basin characteristics for the 55 stream-gaging stations in table 4. Thirty basin characteristics—including those related to climate, soil, and vegetation—were evaluated as possible explanatory variables (not shown). All possible combinations of linear and power regressions using the selected basin characteristics were tested to identify the most robust and significant relations. The regional regressions in table 5 were selected because they had the lowest residual sum of squares and met the following criteria. First, all regression coefficients were statistically significant at a 5-percent significance level. Second, the sign and magnitude of the fitted coefficients were physically meaningful. Finally, the cross-validated results indicated less than 10 percent bias. For leeward catchment zones, wet season runoff-to-rainfall ratios were estimated on the basis of mean wet season rainfall during 1978–2007 (Giambelluca and others, 2013); dry season runoff-to-rainfall ratios were estimated on the basis of mean dry season rainfall during 1978–2007. For windward catchment zones, wet season runoff-to-rainfall ratios were estimated on the basis of mean annual reference ET (Giambelluca and others, 2014) and the percentage of the catchment zone's area with hydrologic soil groups C and D (U.S. Department of Agriculture, 2006a,b,c); dry season runoff-to-rainfall ratios were estimated on the basis of mean dry season reference ET and the percentage of the zone's area with hydrologic soil groups C and D. The performance statistics of the regression equations in table 5 are used to examine the sensitivity of recharge to runoff-to-rainfall ratios (see Sensitivity Analysis).

Table 4. Mean seasonal runoff-to-rainfall ratios for drainage basins of stream-gaging stations on the Islands of Kaua‘i, O‘ahu, and Maui, Hawai‘i.

[See fig. 7 for locations of drainage basins on O‘ahu; n, number of days used for determining minimum flows in the base flow-separation program (Wahl and Wahl, 1995); E, the base flow-separation program (Wahl and Wahl, 1995) was not used to estimate direct runoff because the streamflow measured at station was ephemeral and was assumed to equal direct runoff; mean annual rainfall estimated from Giambelluca and others (2013) and Frazier and others (2016)]

[1]Gaging-station number	Stream/river/gulch/valley	Island	Aspect	Area of drainage basin, in square miles	n	Period of record selected to calculate mean runoff-to-rainfall ratios			Mean runoff-to-rainfall ratio		Mean annual rainfall	
						Start	End	Number of years	Wet season: November through April	Dry season: May through October	During 1978–2007, inches	[2]Difference during selected period of record, percentage of mean during 1978–2007
16028000 (16022000, 16014000)	Waimea River	Kaua‘i	Leeward	43.68	5	1927	1947	21	0.29	0.22	89.0	5.6
16063000 (16100000, 16062000, 16061000)	North fork Wailua River	Kaua‘i	Windward	5.34	4	1957	1984	28	0.63	0.48	199.8	7.4
16068000	East bank of north fork Wailua River	Kaua‘i	Windward	6.24	4	1978	2007	30	0.50	0.27	129.0	0.0
16071500	Left branch ‘Ōpaeka‘a Stream	Kaua‘i	Windward	0.75	4	1978	2007	30	0.22	0.09	100.5	0.0
16089000 (16088000, 16087000)	Anahola Stream	Kaua‘i	Windward	5.45	4	1956	1985	30	0.48	0.35	108.4	5.2
16097500	Halaulani Stream	Kaua‘i	Windward	1.20	4	1978	2007	30	0.62	0.41	115.0	0.0
16103000	Hanalei River	Kaua‘i	Windward	18.51	4	1993	2007	15	0.57	0.34	175.4	-8.1
16108000	Wainiha River	Kaua‘i	Windward	10.44	5	1978	2007	30	0.54	0.39	207.6	0.0
16114000	Limahuli Stream	Kaua‘i	Windward	1.37	4	1995	2005	11	0.35	0.21	116.5	-2.3
16115000	Hanakāpī‘ai Stream	Kaua‘i	Windward	2.75	5	1941	1949	9	0.41	0.28	128.7	1.2
16116000	Hanakoa Stream	Kaua‘i	Windward	1.09	5	1939	1947	9	0.53	0.31	105.8	1.9
16117000	Kalalau Stream	Kaua‘i	Leeward	1.60	5	1932	1948	17	0.24	0.09	80.5	4.4
16130000	Nahomalu Valley	Kaua‘i	Leeward	3.79	E	1964	1971	8	0.04	0.01	36.6	26.7
16200000	North fork Kaukona-hua Stream	O‘ahu	Leeward	1.38	4	1978	2007	30	0.48	0.49	232.4	0.0
16201000	Right bank of north fork Kaukonahua Stream	O‘ahu	Leeward	1.15	4	1940	1951	12	0.34	0.36	213.4	4.6
16208000	South fork Kaukona-hua Stream	O‘ahu	Leeward	4.10	5	1978	2007	29	0.32	0.28	168.9	0.0
16211600	Mākaha Stream	O‘ahu	Leeward	2.12	5	1978	2007	30	0.13	0.04	71.2	0.0
16212800	Kīpapa Stream	O‘ahu	Leeward	4.25	4	1978	2004	27	0.19	0.13	178.3	0.3
16216000	Waiawa Stream	O‘ahu	Leeward	25.19	4	1978	2004	27	0.21	0.12	93.7	0.3
16226200	North Hālawa Stream	O‘ahu	Leeward	4.02	5	1983	2007	24	0.19	0.10	111.8	-2.8

Table 4.—Continued

[1]Gaging-station number	Stream/river/gulch/ valley	Island	Aspect	Area of drainage basin, in square miles	n	Period of record selected to calculate mean runoff-to-rainfall ratios			Mean runoff-to-rainfall ratio		Mean annual rainfall	
						Start	End	Number of years	Wet season: November through April	Dry season: May through October	During 1978–2007, inches	[2]Difference during selected period of record, percentage of mean during 1978–2007
16228000	Moanalua Stream	O‘ahu	Leeward	2.71	4	1949	1978	30	0.15	0.07	117.8	3.1
16229300	Kalihi Stream	O‘ahu	Leeward	5.21	4	1978	2003	26	0.21	0.11	97.6	-1.1
16244000	Pūkele Stream	O‘ahu	Leeward	1.15	5	1953	1982	30	0.14	0.08	114.6	3.6
16270500	Kamo‘oali‘i Stream	O‘ahu	Windward	3.20	3	1967	1976	9	0.18	0.06	82.8	2.9
16278000	‘Ioleka‘a Stream	O‘ahu	Windward	0.32	3	1944	1968	25	0.09	0.07	95.8	0.4
16283000	Kahalu‘u Stream	O‘ahu	Windward	0.28	3	1941	1970	30	0.11	0.08	119.2	2.9
16303000 (16302000)	Punalu‘u Stream	O‘ahu	Windward	2.78	4	1978	2006	29	0.21	0.13	186.6	0.4
16304200	Kaluanui Stream	O‘ahu	Windward	1.09	4	1978	2007	30	0.34	0.25	168.4	0.0
16325000	Kamananui Stream	O‘ahu	Leeward	3.15	4	1971	2000	30	0.29	0.15	132.0	0.0
16345000	‘Ōpae‘ula Stream	O‘ahu	Leeward	3.00	4	1978	2007	30	0.37	0.24	164.6	0.0
16500100	Kepuni Gulch	Maui	Leeward	1.93	E	1963	1972	10	0.04	0.01	33.1	35.1
16501200	‘Ohe‘o Gulch	Maui	Leeward	8.53	4	1990	1997	8	0.38	0.25	249.4	0.7
16508000	Hanawī Stream	Maui	Windward	3.29	4	1978	2007	30	0.42	0.24	248.7	0.0
16510000	Kapā‘ula Gulch	Maui	Windward	1.35	4	1933	1962	30	0.61	0.38	257.3	1.2
16515000	Waiohue Gulch	Maui	Windward	0.74	4	1933	1962	30	0.52	0.32	247.9	1.3
16516000	Kopiliula Stream	Maui	Windward	3.56	4	1938	1957	20	0.43	0.24	197.8	3.4
16517000	East Wailuaiki Stream	Maui	Windward	3.14	4	1928	1957	30	0.58	0.35	201.2	4.7
16518000	West Wailuaiki Stream	Maui	Windward	3.59	4	1978	2007	30	0.64	0.39	183.5	0.0
16520000	East Wailuanui Stream	Maui	Windward	0.53	4	1928	1957	30	0.75	0.55	228.1	5.4
16527000	Honomanū Stream	Maui	Windward	2.94	4	1939	1963	25	0.55	0.45	149.8	3.7
16552800	Waikamoi Strream	Maui	Windward	2.50	4	1957	1967	11	0.17	0.12	62.9	3.5
16557000	Alo Stream	Maui	Windward	0.47	4	1928	1957	30	0.75	0.65	209.3	2.0
16565000	Ka‘aiea Gulch	Maui	Windward	0.68	4	1933	1962	30	0.50	0.44	216.5	-0.5
16566000	‘O‘opuola Stream	Maui	Windward	0.25	4	1931	1957	27	0.64	0.54	189.4	-0.8
16570000	Na‘ili‘ilihaele Stream	Maui	Windward	3.69	5	1945	1974	30	0.60	0.50	181.9	-1.7
16577000	Kailua Stream	Maui	Windward	2.41	4	1928	1957	30	0.75	0.53	203.4	1.8
16585000	Ho‘olawanui Stream	Maui	Windward	1.34	5	1942	1971	30	0.50	0.32	174.9	-0.7
16586000	Ho‘olawali‘ili‘i Stream	Maui	Windward	0.62	4	1931	1957	27	0.43	0.33	160.2	4.8

Table 4.—Continued

[1]Gaging-station number	Stream/river/gulch/valley	Island	Aspect	Area of drainage basin, in square miles	n	Period of record selected to calculate mean runoff-to-rainfall ratios: Start	End	Number of years	Mean runoff-to-rainfall ratio: Wet season: November through April	Dry season: May through October	Mean annual rainfall: During 1978–2007, inches	[2]Difference during selected period of record, percentage of mean during 1978–2007
16587000	Honopou Stream	Maui	Windward	0.59	4	1978	2007	30	0.57	0.38	145.6	0.0
16604500	ʻĪao Stream	Maui	Windward	6.13	4	1983	2007	24	0.48	0.40	178.1	-3.8
16614000	Waiheʻe River	Maui	Windward	4.27	3	1984	2007	24	0.49	0.45	184.6	-2.4
16618000	Kahakuloa Stream	Maui	Windward	3.40	4	1978	2007	30	0.43	0.33	127.0	0.0
16620000	Honokōhau Stream	Maui	Windward	4.18	4	1978	2007	28	0.35	0.31	200.3	0.0
16636000	Kanahā Stream	Maui	Leeward	1.57	3	1920	1931	11	0.17	0.16	141.8	3.1
16660000	Kūlanihākoʻi Gulch	Maui	Leeward	15.03	E	1963	1970	8	0.01	0.00	22.4	38.6

[1]Data for gaging-station numbers in parentheses were used to reconstruct streamflow at the gaging station whose number is not in parentheses.

[2]For example, mean annual rainfall on the drainage basin of station 16500100 was 35 percent greater during 1963–1972 than that during 1978–2007.

Table 5. Regional-regression equations used to calculate mean seasonal runoff-to-rainfall ratios for catchment zones in ungaged areas on the Island of Oʻahu, Hawaiʻi.

[See fig. 7 for locations of leeward and windward regions on Oʻahu. RMSE, prediction root mean square error; Overall RMSE and percentage bias for the gaged basins on the Islands of Kauaʻi, Oʻahu and Maui used to develop the regional-regression equations; Wet season is November through April; Dry season is May through October; mean wet and dry season rainfall are from Giambelluca and others (2013); mean annual and dry season ETo, reference evapotranspiration, are from Giambelluca and others (2014); % HSG C, percentage of a catchment zone's area that contains hydrologic soil group C; % HSG D, percentage of catchment zone's area that contains hydrologic soil group D; Areas of hydrologic soil groups were derived from U.S.Department of Agriculture (2006a, 2006b, 2006c)]

Region	Season	Regression used to compute runoff-to-rainfall ratio	RMSE: Overall	RMSE: Oʻahu	Percentage bias: Overall	Percentage bias: Oʻahu
Leeward	Wet	0.00320 [mean wet season rainfall]	0.06	0.06	0.6	-3
Leeward	Dry	0.00293 [mean dry season rainfall]	0.07	0.07	3.8	6
Windward	Wet	$[\% \text{ HSG C}]^{0.185} [\% \text{ HSG D}]^{0.247} [\text{mean annual ETo}]^{(-0.590)}$	0.12	0.13	-4.8	28
Windward	Dry	$[\% \text{ HSG C}]^{0.186} [\% \text{ HSG D}]^{0.346} [\text{mean dry season ETo}]^{(-0.947)}$	0.11	0.10	-5.8	23

Runoff-to-Rainfall Ratios Assigned to Gaged Basins within a Single Catchment Zone

Twelve of the selected stream-gaging stations on O‘ahu have drainage basins with a single catchment zone (fig. 7). Four of these stations (16201000, 16270500, 16278000, and 16283000) were not operational during 1978–2007 (table 4). For the drainage basins of these four stations, direct runoff was calculated using mean seasonal runoff-to-rainfall ratios. For the drainage basins of the eight remaining stations (16200000, 16208000, 16211600, 16244000, 16303000, 16304200, 16325000, and 16345000), direct runoff was calculated using (1) observed seasonal runoff-to-rainfall ratios for seasons when observed ratios were available, and (2) mean seasonal runoff-to-rainfall ratios for seasons when observed ratios were not available.

Runoff-to-Rainfall Ratios Assigned to Gaged Basins with Multiple Catchment Zones

Five of the selected stream-gaging stations on O‘ahu (16212800, 16216000, 16226200, 16228000, and 16229300) have drainage basins containing multiple catchment zones (fig. 7). Direct runoff for each of the catchment zones within these gaged basins was calculated using adjusted seasonal runoff-to-rainfall ratios determined from equation 17:

$$\widetilde{rr}_{a,t} = \widetilde{RR}_a \times \frac{rr_{b,t} \times rf_{b,t}}{\sum_{i=1}^{j} \widetilde{RR}_i \times rf_{i,t}} \qquad (17)$$

where

$\widetilde{rr}_{a,t}$ = adjusted runoff-to-rainfall ratio for catchment zone *a* during season *t*,

$\widetilde{RR}_a$ = mean runoff-to-rainfall ratio for catchment zone *a* estimated using the appropriate regional-regression equation (table 5),

j = number of catchment zone in the gaged basin *b*,

$\widetilde{RR}_i$ = mean runoff-to-rainfall ratio for catchment zone *i* estimated using the regional- regression equations,

$rf_{i,t}$ = rainfall for catchment zone *i* during season *t*,

$rf_{b,t}$ = rainfall for gaged basin *b* during season *t*, and

$rr_{b,t}$ = observed runoff-to-rainfall ratio for the gaged basin *b* during season *t*. If the observed runoff-to-rainfall ratio for gaged basin *b* is not available during season *t*, the mean seasonal runoff-to-rainfall ratio is used (table 4).

Equation 17 uses the regional-regression models and seasonal rainfall to spatially disaggregate observed seasonal and mean seasonal runoff-to-rainfall ratios of a gaged basin for each catchment zone within a gaged basin. Hence, seasonal runoff-to-rainfall ratios were allowed to be spatially variable, instead of spatially uniform, across the catchment zones within gaged drainage basins containing multiple catchment zones.

Evapotranspiration

Evapotranspiration (ET) is the sum of all water that is evaporated or transpired from a vegetated surface and plant-root zone. Evapotranspiration can be divided into three main evaporative processes (1) canopy evaporation, which is evaporation of intercepted rain and fog from the surface of vegetation; (2) ground evaporation, which is evaporation of water from the soil surface and overlying litter and mulch layers; and (3) transpiration, the process by which soil moisture taken up by vegetation is eventually evaporated through plant pores (Viessman and Lewis, 2003). Because these three processes are difficult to quantify individually, they are typically combined in water budgets.

Canopy evaporation in forested areas can substantially reduce the rainfall that reaches the ground beneath a forest canopy (Gaskill, 2004; DeLay, 2005; McJannet and others, 2007; Giambelluca and others, 2011; Safeeq and Fares, 2012b). Owing to the height of trees and their canopy structure, turbulent diffusion is much more efficient at removing intercepted water from forest canopies than from shorter vegetation. Moreover, canopy evaporation in forests tends to operate on much shorter time scales (hours) than transpiration (weeks or longer) (Savenije, 2004). This enhanced rate of evaporation from a wet forest canopy makes realistic estimates of ET from forests possible only if transpiration and canopy evaporation are evaluated separately (Shuttleworth, 1993).

For this study, total ET from subareas with forest land covers is calculated by separately estimating forest-canopy evaporation and combined ground evaporation and transpiration from the plant-root zone (fig. 5). Evaporation from the forest canopy and evapotranspiration from the plant-root zone are added together to yield total ET. For subareas with nonforest land covers, ET is calculated using a more traditional approach in which canopy evaporation, ground evaporation, and transpiration are not separately estimated (fig. 5). The concept of potential ET, combined with empirical models when soil moisture is limited, is used to estimate ground evaporation and transpiration for forest land covers and total ET for all other land covers.

Forest-Canopy Evaporation and Net Precipitation

As rain falls on a vegetated surface, a fraction of the droplets will accumulate on the leaves, trunks, or stems of the vegetation. Additional moisture from fog interception may supplement the amount of water that accumulates on vegetation. Canopy evaporation is the part of precipitation that accumulates on and then evaporates from the vegetation (Gerrits and Savenije, 2011). Net precipitation is the part of precipitation that reaches the forest floor (fig. 5).

In this study, the Gash model was used to calculate forest-canopy evaporation for the following reasons. First, the Gash model accounts for gaps in the forest canopy, and this allows for a sparse canopy to be differentiated from a dense canopy. Second, canopy evaporation during a period of precipitation is dependent on the amount of precipitation during that period. Third, the Gash model has the capacity to account for spatial differences in climate, including climate differences between windward and leeward forests. One disadvantage of the Gash model, however, is that it is theoretical. Therefore, one of the parameters of the Gash model used to calculate canopy evaporation in the water-budget model was calibrated to the wet-canopy evaporation maps of Giambelluca and others (2014) as described below. Use of the Gash model, instead of the mean wet-canopy evaporation maps, in the water-budget model allows forest-canopy evaporation to be calculated on a daily basis in response to daily variations in precipitation.

Forest-canopy evaporation is calculated in the water-budget model according to equations 4 and 5, which require values for rainfall and the following five parameters (1) canopy cover, (2) canopy capacity, (3) trunk-storage capacity, (4) proportion of precipitation diverted to stemflow, and (5) the ratio of the mean evaporation rate to mean precipitation rate during saturated conditions, V. For the water-budget calculations, the values assigned to parameters 1–4 were derived from published data for areas in Hawai‘i. The values assigned to V were derived using maps of mean wet-canopy evaporation for the Islands of Kaua‘i, O‘ahu, and Maui (Giambelluca and others, 2014).

Canopy cover of forest land-covers varies spatially across O‘ahu. The canopy cover of each subarea with forest land cover in the water-budget model was estimated from a map of mean annual vegetation cover fraction (Giambelluca and others, 2014). This map quantifies the vegetation cover fraction at a spatial resolution of about 14 acres. A canopy cover of 0 implies an absence of canopy cover, whereas a value of 1 implies a dense canopy with no gaps. The estimated canopy-cover values for subareas with forest land covers used in the water-budget model range from 0.03 to 1.

Canopy capacity, trunk-storage capacity, and the proportion of precipitation diverted to stemflow were assumed to be the same for all forests (table 6). Canopy capacity was set at 0.05 inches, the mean of the average values reported for six forested sites in Hawai‘i (DeLay, 2005, p. 42; Takahashi and others, 2011, Safeeq and Fares, 2012b). Trunk-storage capacity was set at 0.01 inches, the mean of the values reported for four forest sites in Hawai‘i (DeLay, 2005, p. 42; Safeeq and Fares, 2012b). The proportion of precipitation diverted to stemflow was assumed to be 0.04, the mean of the values reported for eight forest sites in Hawai‘i (Gaskill, 2004; DeLay, 2005, p. 42; Takahashi and others, 2011; Safeeq and Fares, 2012b). Forest sites of Takahashi and others (2011) and Safeeq and Fares (2012b) with an abundance of *Psidium cattleianum* (strawberry guava) had relatively high stemflow estimates ranging from 29 to 34 percent of rainfall. In order to have conservative stemflow estimates in the water budget, the high stemflow values from these sites were excluded from the calculated stemflow mean of 0.04 used in the water budget.

A map of mean annual wet canopy evaporation for the Hawaiian Islands (Giambelluca and others, 2014) was used to develop a regression model for estimating the spatial variability of V. This regression model was developed because estimates of V for sites in Hawai‘i are rare, and because canopy-evaporation estimates from the water-budget model are sensitive to V. The wet canopy evaporation map has mean annual wet canopy evaporation estimates at a spatial resolution of about 14 acres. To derive a regression model for estimating V, we first selected grid cells from the islands of Kaua‘i, O‘ahu, and Maui that consisted of forest land-cover classes only, based on the LANDFIRE Existing Vegetation Type map (U.S. Geological Survey, 2010). Data from Kaua‘i and Maui were included in the analysis to supplement the data from O‘ahu and to provide the basis for a broadly applicable V value for Hawai‘i. Next, for each of the selected grid cells, the calibrated V value needed for mean annual canopy evaporation from the Gash model for Kaua‘i, O‘ahu, and Maui to equal that of the wet canopy evaporation map of Giambelluca and others (2014) was determined. The Gash model was used with various V values to determine the calibrated V values for the selected grid cells. Last, associations between the calibrated V values and various other parameters of the selected grid cells, including estimates of mean annual rainfall, reference ET, Penman-Monteith ET from Giambelluca and others (2014), and estimates of mean annual wind speed from AWS Truewind, LLC (2004) were determined.

Estimates of V from a linear regression model (equation 18) relating V to the quotient of mean annual wind speed and mean annual rainfall resulted in the best agreement, in terms of bias and root mean square error, between estimates of canopy evaporation from the wet canopy evaporation maps (Giambelluca and others, 2014) and the estimates from the Gash model for Kaua‘i, O‘ahu, and Maui. The spatial distribution of V was estimated as follows:

for $w < 0.009$,

$$V = 0.01,$$

for $0.009 \leq w \leq 0.192$,

$$V = 2.677 \times (w) - 0.014, \text{ and}$$

for $w > 0.192$,

$$V = 0.50, \qquad (18)$$

where

w = mean annual wind speed divided by mean annual rainfall (m/s/in).

The variable w is the quotient of (1) mean annual wind speed, in meters per second, which was derived from a map of mean annual wind speed at height of about 100 ft above the land surface (AWS Truewind, 2004), and (2) 1978–2007 mean annual rainfall, in inches

Table 6. Land-cover parameters used in water-budget calculations for the Island of Oʻahu, Hawaiʻi.

[Crop coefficients for forests are used to compute the sum of transpiration and ground evaporation; canopy evaporation is computed separately. Crop coefficients for nonforest land covers are used to compute the sum of all evaporative components; All water bodies, includes water bodies, reservoirs, and estuarine/near-coastal water bodies]

Land-cover description		Root depth, in inches	Depletion fraction	Crop coefficient	Canopy capacity, in inches	Trunk-storage capacity, in inches
Forest land covers						
Alien forest		60	0.50	[a]0.33, [b]0.44	0.05	0.01
Native forest		30	0.50	0.30	0.05	0.01
Kiawe/Phreatophytes		71	1.00	0.84	0.05	0.01
Tree plantation		60	0.50	[a]0.33, [b]0.44	0.05	0.01
Nonforest land covers						
Agriculture—						
	Coffee	48	0.40	0.91	0	0
	Corn	18	0.60	[c]0.29–1.20	0	0
	Diversified	10	0.35	1.00	0	0
	Fallow/grassland	39	0.60	0.95	0	0
	Macadamia	60	0.50	0.91	0	0
	Pineapple	18	0.50	0.30	0	0
	Taro	10	1.00	1.05	0	0
Developed—						
	Low-intensity	12	0.50	1.18	0	0
	Medium-intensity	12	0.50	1.18	0	0
	High-intensity	12	0.50	1.18	0	0
Golf course		30	0.50	0.85	0	0
Grassland		39	0.60	0.95	0	0
Shrubland		12	0.50	1.00	0	0
Sparsely vegetated		5	0.50	1.18	0	0
Wetland		39	0.50	1.18	0	0
All water bodies		1	1.00	1.05	0	0

[a]Value used inside the fog zone, which is above 2,000 feet.

[b]Value used outside the fog zone.

[c]Varies by month (see Crop Coefficients section for explanation).

(Giambelluca and others, 2013). In general, estimates of *V* for wet areas are less than those for dry areas. Grid cells that had calibrated *V* values that were outside the range of 0.01–0.50 were excluded from the derivation of equation 18. A range of 0.01–0.50 was established for this analysis on the basis of the range of published estimates of *V*. The low end of the range, 0.01, was determined by Hutjes and others (1990) for a humid, tropical forest site in the Ivory Coast. The high end of the range, 0.50, is the mean value reported by Safeeq and Fares (2012b) for a forest site on leeward Oʻahu. A similar range of mean *V* estimates (about 0.03–0.40) was determined for 54 sites located in various climate zones across Australia (Wallace and others, 2013, fig. 6c). An analysis of the sensitivity of the water-budget results to selected Gash-model parameters is included in the Sensitivity Analysis section of this report.

Potential Evapotranspiration

Potential evapotranspiration (ET) is the maximum rate that water can be removed from the plant-root zone by ET if soil moisture is nonlimiting (Giambelluca, 1983). The actual-ET rate is a function of potential ET, soil-moisture content, and threshold-moisture content (see equation 13). The actual-ET rate becomes less than the potential rate with the onset of soil-moisture stress. As the soil dries, capillary and adsorptive forces bind the remaining water to the soil matrix, reducing water flow to roots. Soil-moisture stress occurs when the decreasing flow of water to the root system induces a response in the plant to slow down transpiration and prevent desiccation. The threshold-moisture content at which a plant begins to react to soil drying varies with the type of plant.

Potential ET is controlled by atmospheric conditions, topography, and land-cover characteristics (Giambelluca, 1983). Maps of mean monthly reference ET produced by Giambelluca and others (2014) were used in the water-budget model to estimate the influence of atmospheric conditions (radiation, air temperature, air humidity, and wind speed) on potential ET. Crop coefficients were used to estimate the integrated effects of land-cover and vegetation characteristics on potential ET. Potential ET for each subarea was calculated in the water-budget model as the product of mean monthly reference ET and the crop coefficient assigned to the land cover, and was assumed to be constant within a given month (see equation 9).

Reference Evapotranspiration

Reference ET, as defined in this study, is the potential ET of a hypothetical grass surface with specific characteristics and optimum soil-water conditions for given climatic conditions and is equivalent to FAO Penman-Monteith ET (Allen and others, 1998). Reference ET is similar to pan evaporation, which has been used in previous water budgets for Maui and other Hawaiian Islands. Both pan evaporation and reference ET provide an index of the energy that is available for ET for a given area.

Maps of mean monthly reference ET (Giambelluca and others, 2014) for O‘ahu were used in the water budget. These maps have the same grid resolution (about 14 acres) as the monthly rainfall maps. Mean annual reference ET ranges from about 32 to 112 in on O‘ahu (fig. 8). In general, mean annual reference ET is highest in dry lowland areas, and is lowest in wet upland areas within the cloud zone. In the water-budget calculation, monthly reference ET was not varied from year to year, and was assumed to equal mean monthly reference ET. Reference ET was assumed to be the same each day of a given month.

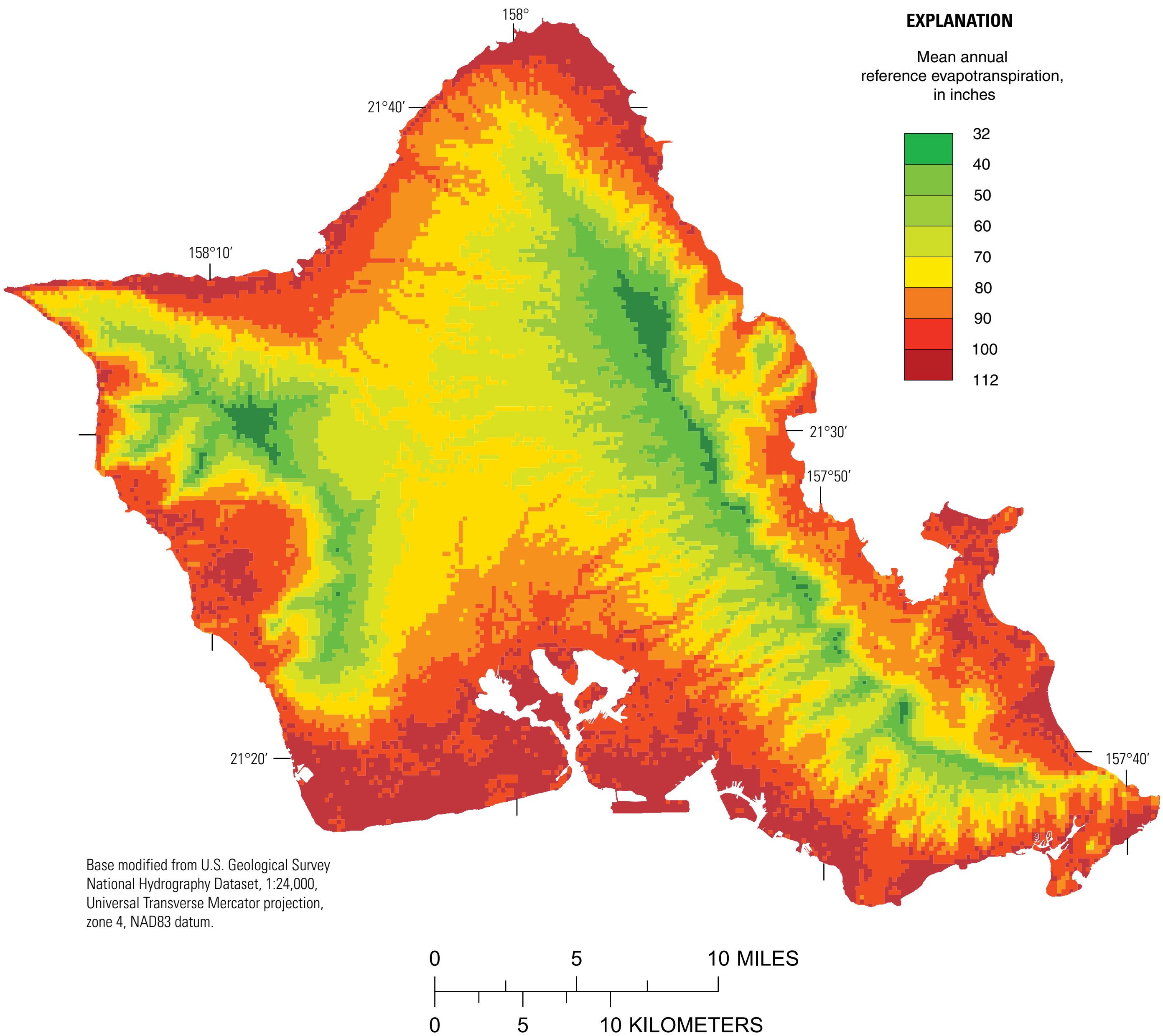

Figure 8. Mean annual reference evapotranspiration for the Island of O‘ahu, Hawai‘i (modified from grass reference evapotranspiration in Giambelluca and others, 2014).

Crop Coefficients

A crop coefficient is an empirically derived ratio of the potential ET of a certain type of land cover and reference ET. Crop coefficients provide an index of the integrated effect of vegetation characteristics (reflectance, roughness, and plant physiology) on potential ET. Crop coefficients were assigned to each land-cover class (table 6). Crop coefficients were assumed to be temporally constant for all classes other than corn. For nonforest land-cover classes, crop coefficients integrated the effects of transpiration, ground evaporation, and canopy evaporation. For forested land-cover classes, crop coefficients integrated the effects of transpiration and ground evaporation; canopy evaporation was accounted for separately (fig. 5).

Crop coefficients for nonforest land covers (table 6) were obtained from published values or were derived from pan coefficients used for the same or similar land-cover classes in previous water budgets for Hawai‘i. A Hawai‘i pan coefficient for a given land cover is the ratio of potential ET to pan evaporation. Hence, pan coefficients are analogous to crop coefficients. Pan coefficients for land-covers other than sugarcane were converted to crop coefficients by dividing the pan coefficients by 0.85, a factor that Engott (2011) used to convert crop coefficients to pan coefficients. Crop coefficients for grassland, pineapple, taro, wetland, water body, and reservoir land covers were obtained from Allen and others (1998). The midpoint of the range of crop coefficients for grazing pasture (rotated grazing) was used for grassland. The mean of the crop coefficients for wetlands with no frost was used for wetland. The crop coefficient for open water in the tropics was used for taro, water body, and reservoir land covers. Crop coefficients for coffee and macadamia were obtained from Fares (2008). Crop coefficients for golf course and the developed land covers were derived from the pan coefficient used by Engott (2011) for developed land covers. Crop coefficients for diversified agriculture, shrubland, and sparsely vegetated land were also derived from pan coefficients used by Engott (2011). The crop coefficients for corn vary monthly and are based on information in the Hawaii Agricultural Water Use and Development Plan (University of Hawai‘i, 2008). The crop coefficients used for corn were 0.85, 0.50, 0.29, 0.40, 0.80, 1.20, 0.85, 0.50, 0.29, 0.40, 0.80, and 1.20 for the months of January through December, respectively.

Maps of mean soil (ground) evaporation and transpiration (Giambelluca and others, 2014) were used to derive crop coefficients for forest land covers. First, the water budgets for Kaua‘i, O‘ahu, and Maui were calculated using a range of crop coefficients for forest land covers. Next, the sum of ground evaporation and transpiration was determined for subareas on Kaua‘i, O‘ahu, and Maui with (1) native forest land cover inside of the cloud zone, (2) native forest land cover outside of the cloud zone, (3) alien forest land cover inside of the cloud zone, and (4) alien forest land cover outside of the cloud zone. The crop coefficients listed in table 6 resulted in the best match, in terms of ground evaporation plus transpiration, between the maps of Giambelluca and others (2014) and subareas with forest land covers in water budgets of Kaua‘i, O‘ahu, and Maui. The derived crop coefficient for alien forests within the cloud zone is less than that for alien forests outside the cloud zone. This difference could be related to spatial differences in tree species or reduced transpiration with the presence of fog. The crop coefficients for alien forests are also used for tree plantations. For native forests, one crop coefficient is used because the crop coefficient estimated for areas inside the cloud zone is nearly identical to that for areas outside of the cloud zone.

Moisture-Storage Capacity of the Plant-Root Zone

The moisture-storage capacity of the plant-root zone (fig. 9) was calculated as the product of available water capacity and root depth (equation 12). The USDA (2006a) soil map and corresponding tables of available water capacities were used to quantify the available water capacity of the soils on O‘ahu. For each soil unit, the tables list the minimum and maximum available water capacities for various ranges of depth. A depth-weighted mean available water capacity was calculated for each soil type in the water-budget model. However, all depths of the soil unit “rock outcrop” have zero available water capacity according to tables of USDA (2006a). For this study, zero available water capacity for the “rock outcrop” soil unit was considered too low because many areas with this soil unit on O‘ahu were mapped as grassland or shrubland. Therefore, for the water-budget calculations, available water-capacity values for the “rock land” soil unit were used for all subareas with the “rock outcrop” soil unit. The soil unit “rock land” was selected because it generally was mapped near “rock outcrop” soils and because its available water capacity exceeds zero in the top eight inches of soil. Subareas with water body and reservoir land covers have zero available water capacity at all soil depths and therefore have zero soil-moisture storage capacity (fig. 8).

Root depths for each land-cover class were assigned values on the basis of published values and root depths used in previous water budgets in the Hawaiian Islands (table 6). The root depth used for pineapple is the middle of the range of pineapple root depths reported in Fares (2008) and Allen and others (1998). The root depth used for diversified agriculture is near the middle of the range reported in Fares (2008) for typical diversified agriculture crops in the Hawaiian Islands. The root depth used for taro is the middle of the range reported in Fares (2008). The root depth used for wetland is the same as that used for grassland. For all other land-cover classes, the root depths used are the same as those used by Engott (2011) in the water budget for the Island of Hawai‘i.

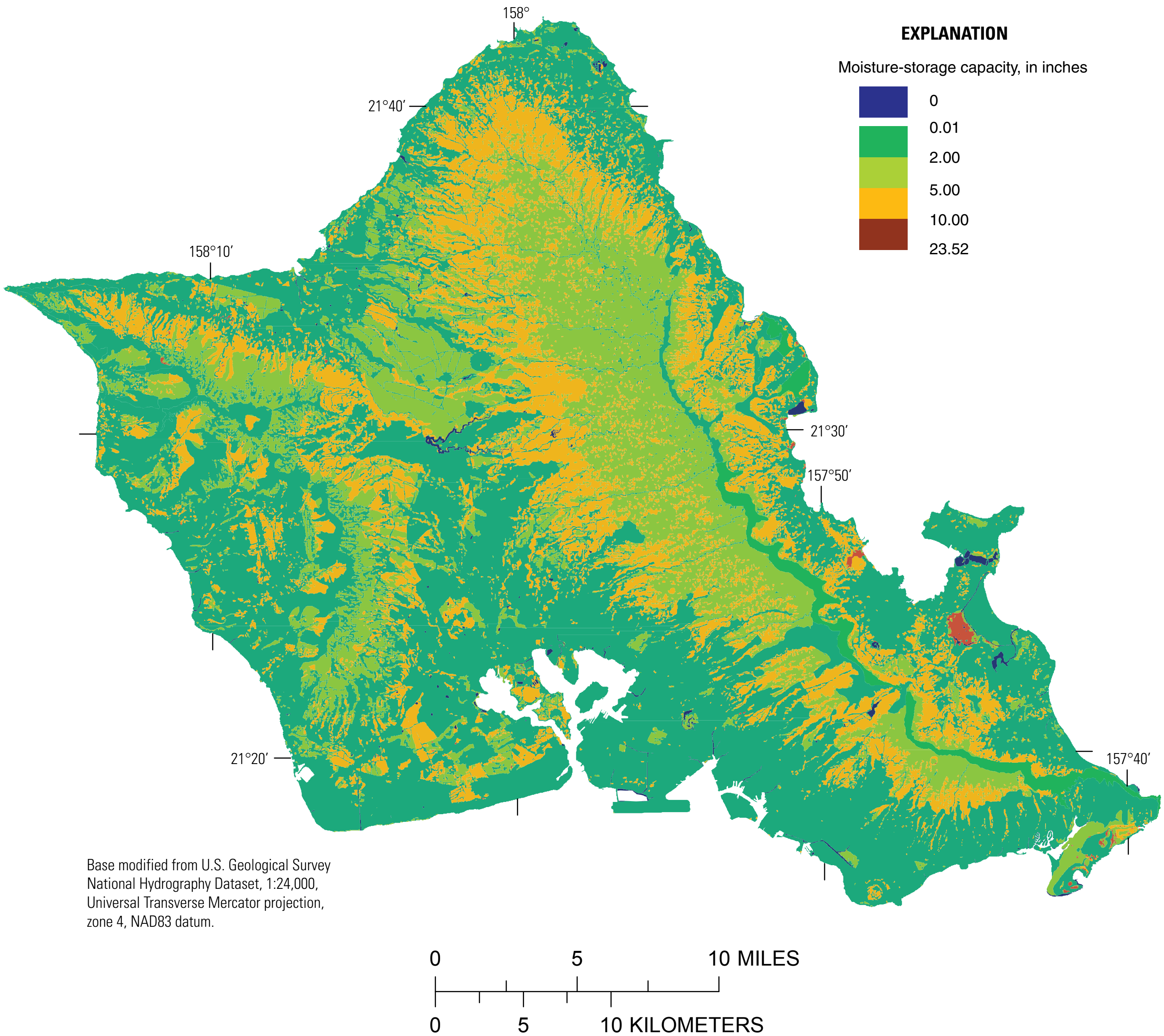

Figure 9. Calculated moisture-storage capacity of the plant-root zone, Island of O‘ahu, Hawai‘i.

Direct Recharge

For this study, direct recharge is defined as water that passes directly to the groundwater system, completely bypassing the plant-root zone (equation 15). Hence, direct recharge is not subject to direct runoff or ET processes. Direct recharge was estimated for subareas with water mains, cesspools and land covers that are typically saturated—taro, water bodies and reservoirs, and estuarine/near-coastal water bodies (fig. 4). For subareas within TMK parcels with cesspools, the wastewater effluent fluxes estimated by Whittier and El-Kadi (2009) were applied as direct recharge (see Septic-System Leaching section). The direct recharge rate from water bodies was set at 64 in/yr, on the basis of seepage estimates in Dugan and others (1975). For reservoirs, the direct recharge was set to 528 in/yr, which has been used in recent water budgets for Hawai‘i (Engott and Vana, 2007; Engott, 2011). For estuarine/near-coastal water bodies, the recharge rate was set to zero, because these water bodies were assumed to produce no net recharge.

Water-main leakage is another source of direct recharge. Water-main leakage on O‘ahu was estimated on the basis of maps and information supplied by the Honolulu Board of Water Supply. A detailed spreadsheet of water-main leaks and breaks on O‘ahu in 2007 (Carolyn Sawai, Honolulu Board of Water Supply, written commun., 2012) was used to estimate an average annual rate of water-main leakage. The total amount of water-main leakage on Oʻahu was estimated to be about 1.75 Mgal/d and was applied at a uniform rate, 0.01 in/day, along the length of each water main. The area subject to leakage was assumed to be 1 m on either side of a water-main centerline. A leakage rate of 1.75 Mgal/d is about 1.2 percent of the average system flow rate, which is substantially lower than the typical average rate for a municipal water system—about 10 percent (State of California, 2014). However, using the lower rate is conservative with regard to recharge estimation. The effect of using an estimate of water-main leakage consistent with 10 percent of average water-system flow is addressed in the Sensitivity Analysis section of this report.

Other Input

In addition to the water-budget inputs already listed, several other input parameter values were required. The initial moisture storage for the pervious fraction of subareas was set at 50 percent of the soil moisture-storage capacity. The rainfall-retention capacity for impervious surfaces was assumed to be 0.25 in. The initial moisture storage for the impervious fraction of subareas was set at 0.125 in, which is calculated as 50 percent of the rainfall-retention capacity of 0.25 in. These values were also used for other recent Hawaiʻi water budgets (Izuka and others, 2005; Engott and Vana, 2007; Engott, 2011). The effects of these inputs on regional-scale mean annual recharge generally are minor because they either pertain to only a small area or are applicable during only a small fraction of time.

Model Exclusions and Limitations

Several exclusions were made to simplify the water-budget model. Re-infiltration of direct runoff, water that runs off one subarea and then infiltrates the plant-root zone of a different subarea, was not explicitly considered in the water-budget model. Re-infiltration of direct runoff within gaged basins was assumed to be included in streamflow records used to derive runoff-to-rainfall ratios. Spatial variations in the re-infiltration of direct runoff within a drainage basin, however, were not accounted for in the model. For example, if re-infiltration of direct runoff was considerable within streambeds, then recharge may have been underestimated in intra-channel (streambed) areas and overestimated in inter-channel (nonstreambed) areas. Additionally, direct runoff from upland areas that seeps into the streambed of lower reaches near the coast was not quantified. Surface-water diversion systems, however, can reduce or prevent streambed seepage in lower reaches of certain streams on Oʻahu.

Owing to the sparseness of data and the use of synthesized daily rainfall, the water-budget model did not reconstruct the actual distributions of the water-budget components (rainfall, fog interception, irrigation, septic-system leachate, runoff, evapotranspiration, and recharge) on Oʻahu for each simulated day. The reconstruction of actual daily runoff was also prevented by the use of seasonal runoff-to-rainfall ratios. Additionally, runoff may have been overestimated by the model on days with light rain and underestimated on days with intense rain. The water-budget model did, however, reproduce the spatial distribution of (1) monthly rainfall on Oʻahu during 1978–2007 that was estimated by Frazier and others (2016), and (2) mean monthly and mean annual rainfall on Oʻahu during 1978–2007 that was estimated by Giambelluca and others (2014). For gaged drainage basins, the water-budget model reproduced seasonal runoff estimates that were based on streamflow measurements at stream-gaging stations.

Some parameters and conditions not included in the calculations of the water-budget model were inherent in other parameters used in the model. For example, the permeability and vertical hydraulic conductivity of the plant-root zone and underlying substrate were not included in the model calculations. Their effect on direct runoff, however, would be inherent in streamflow records used to derive runoff-to-rainfall ratios that were used to calculate direct runoff in the model. For subareas with forest land covers, a reduction in the potential ET of the plant-root zone in response to evaporation from the forest canopy was not included in the model calculations. However, the effects of forest-canopy evaporation on the potential-ET rate likely were accounted for in the forest crop coefficients, which were calibrated to the maps of mean transpiration and ground evaporation produced by Giambelluca and others (2014).

Some processes and conditions were excluded from the water-budget calculations. Potential ET was assumed to be uniform each day of the month and consequently may have been overestimated on cloudy days and underestimated on clear days. For subareas with impervious surfaces, potential ET was not reduced to account for evaporation from impervious surfaces. Adjustments to reference ET at scales less than the spatial resolution of the reference ET maps, such as those related to shading in rugged terrain, were not accounted for in the model. Other conditions not considered in the model include the variability of soil moisture with regard to depth within the soil root zone, the effect of soil texture on irrigation demand, and removal of water from saturated groundwater zones by transpiration. Additionally, daily irrigation estimates were based on monthly variations in rainfall, runoff, and potential ET instead of daily variations. The daily irrigation estimates of the water-budget model may also differ from actual irrigation rates because, in addition to the model not reproducing actual daily rainfall, the model does not account for other factors—such as field observations, nonirrigation water needs, and water availability—that may be considered by irrigation managers each day.

Datasets for calibrating recharge estimates of the model were not available. ET estimates of the model for forested areas, however, were calibrated to maps of actual ET produced by Giambelluca and others (2014). Additionally, runoff was estimated using an empirical model derived from streamflow records.

Water-Budget and Groundwater-Recharge Estimates

The water-budget model was used to calculate recharge for two scenarios: average climate conditions and drought conditions. Monthly rainfall during 1978–2007 was used for the average-climate-conditions scenario. Monthly rainfall during 1998–2002 was used for the drought-conditions scenario. Both scenarios used 2010 land cover and mean monthly reference evapotranspiration. Water-budget estimates for average climate conditions are compared with previous estimates.

Water-Budget and Recharge Estimates for Average Climate Conditions

For the Island of Oʻahu, mean annual recharge is about 660 Mgal/d for average climate conditions (table 7). Recharge is about 36 percent of precipitation and is about 34 percent of total inflow (sum of rainfall, fog interception, irrigation, septic leachate, and direct recharge). Direct recharge, which consists of leakage from water mains and seepage from reservoirs and cesspools, accounts for about 3 percent of overall recharge. Expressed as a depth of water uniformly distributed across the island, mean annual recharge is about 23 in. Mean annual recharge, in inches, is highest in the Central aquifer sector and lowest in the Waiʻanae aquifer sector (table 7).

The spatial pattern of mean annual recharge on Oʻahu for average climate conditions resembles that of mean annual rainfall, but also reflects (1) spatial variations in vegetation and soils, (2) irrigation in agricultural and developed areas, (3) seepage from reservoirs, and (4) persistent cloud layers where fog interception supplements rainfall (fig. 10). Recharge is high along the crest of the Koʻolau Range, reaching as much as about 180 in/yr in the north-central part of the range. Relatively high recharge rates also occur in the higher elevations of the Waiʻanae Range, reaching as much as about 60 in/yr near the summit of Mt. Kaʻala. Recharge is much lower outside of the mountainous areas of the island. In undeveloped and nonagricultural areas at low elevation, recharge is commonly less than 5 in/yr. Detectable at these lower elevations are the footprints of irrigated agricultural fields and golf courses, which contribute higher rates of recharge than adjacent, unirrigated areas. Also detectable are small areas of very high recharge, which generally correspond to taro cultivation, reservoirs, or areas of high cesspool usage.

The estimated fraction of total water inflow that becomes groundwater recharge is shown in figure 11. For most of Oʻahu, the fraction is less than 40 percent. Apart from areas of taro cultivation and reservoirs, which have a fraction of 100 percent by definition, the areas with the highest fraction, over 60 percent, occur in the high rainfall areas of the Koʻolau Range. This roughly corresponds to the areas with high recharge. The consistently wet conditions keep the soil moisture high. Some notable areas with a fraction over 40 percent include (1) the wetter, higher elevations of the Waiʻanae Range; (2) the pineapple fields of central Oʻahu, where the low transpiration rate of the crop is responsible; and (3) patches of the ʻEwa Plain and leeward coast, where a combination of very low rates of runoff (fig. 7), low soil moisture storage capacity (fig. 9), and low total water inflow is responsible.

Comparison with the Water Resources Protection Plan

The 1990 Water Resources Protection Plan (WRPP; State of Hawaiʻi, 1990) included recharge estimates, in Mgal/d, for all aquifer systems on Oʻahu. Although not listed in the document, the 2008 WRPP (State of Hawaiʻi, 2008) used the same recharge values as the 1990 WRPP for most aquifer systems. However, recharge estimates for some aquifer systems were updated and some aquifer systems, as delineated in the 1990 WRPP, were split and (or) combined in the 2008 WRPP. Recharge estimates used in the 2008 WRPP were provided by the State Commission on Water Resource Management (CWRM; Roy Hardy, written commun., May 2014) .

Recharge estimates reported in the 1990 WRPP were based on a water budget that considered mean annual rainfall, runoff, and ET. For comparison with results from this study, estimates of precipitation, runoff, and ET reported in the 1990 WRPP were converted from units of in/yr to Mgal/d on the basis of the aquifer-system areas provided by CWRM (table 8; Roy Hardy, written commun., May 2014). Because some of the 1990-WRPP aquifer systems were split and (or) combined in the 2008 WRPP, some recombining of aquifer systems, as delineated in the 2008 WRPP, was needed to compare water-budget components from the 1990 WRPP with the results from this study (table 8).

Caprock areas were excluded from the calculation of aquifer-system recharge in the 1990 WRPP. The spatial extent of caprock areas on Oʻahu, however, was not defined in the 1990 WRRP. In the 2008 WRPP, the ʻEwa caprock area was delineated (fig. 1), but other caprock areas were not. To facilitate comparison between recharge estimates from the 2008 WRPP and the estimates of this study, the caprock area was estimated to consist of all areas seaward of the 0-ft elevation contour of the top of the volcanic-rock aquifer (fig. 1). This is water-budget-area description “B” in table 8. Because there was a small difference in the areas, the ʻEwa caprock area, as defined in the 2008 WRPP, was also used to compare study estimates for the Waipahu-Waiawa, ʻEwa-Kunia, and Makaīwa aquifer systems. This is water-budget area description “C” in table 8.

Another complication in comparing recharge estimates from the 2008 WRPP and the estimates of this study concerns the redistribution of high-level recharge from the Wahiawā aquifer system to adjacent aquifer systems. According to the 2008 WRPP, 62 Mgal/d of recharge is allocated to the Waipahu-Waiawa aquifer system, 14 Mgal/d is allocated to the combined ʻEwa-Kunia and Makaīwa aquifer systems, and 41 Mgal/d is allocated to the Waialua aquifer system. The Waialua allocation is calculated from information given in the 2008 WRPP and the recharge estimates provided by CWRM

Table 7. Mean annual water-budget components from this study for average climate and drought conditions for the Island of O‘ahu and for individual aquifer-sector areas.

[See fig. 1 for locations of aquifer sectors; Mgal/d, million gallons per day; in/yr, inches per year; Irr, irrigation; Septic, septic-system leachate; Direct rech, direct recharge; Canopy evap, forest canopy evaporation; Total ET, total evapotranspiration which includes canopy evaporation. Average climate conditions for this study are 1978–2007 rainfall and 2010 land cover; drought conditions for this study are 1998–2002 rainfall and 2010 land cover. Components may not balance because of rounding and direct recharge from cesspools and reservoirs. The source of water for direct recharge may be from external sources, including groundwater and imported streamflow. Some recharge may discharge to streams as base flow. Ford and Sand Islands (fig. 2) are not included]

Location	Condition/ Scenario	Area, in square miles	Water-budget component, in Mgal/d										Recharge, in/yr
			Rain	Fog	Irr	Septic	Direct rech	Runoff	Canopy evap	Total ET	Storm drain	Recharge	
Island of O‘ahu	Average climate	595.84	1,821.35	10.63	114.75	1.32	20.71	264.77	237.90	1,015.44	39.96	660.21	23.27
	Drought		1,346.58	7.94	129.21	1.32	20.71	190.48	198.94	894.77	20.23	417.34	14.71
Honolulu aquifer sector	Average climate	84.99	240.61	0.74	19.97	0.04	2.11	28.58	36.52	147.29	15.57	73.62	18.19
	Drought		179.15	0.53	22.31	0.04	2.11	21.08	30.58	131.93	8.38	44.78	11.07
Pearl Harbor aquifer sector	Average climate	162.84	444.08	2.23	54.43	0.04	5.68	59.00	56.70	261.45	13.38	175.54	22.64
	Drought		330.35	1.72	60.54	0.04	5.68	39.16	47.93	234.19	6.39	122.57	15.81
Wai‘anae aquifer sector	Average climate	60.91	111.41	0.79	6.19	0.17	0.87	8.09	13.25	73.20	1.16	37.27	12.85
	Drought		67.90	0.43	6.77	0.17	0.87	4.52	9.12	58.69	0.53	13.18	4.55
North aquifer sector	Average climate	93.94	236.81	0.87	10.72	0.47	5.56	25.28	36.65	161.95	0.00	69.15	15.46
	Drought		168.95	0.47	12.21	0.47	5.56	17.48	29.67	138.99	0.00	34.50	7.71
Central aquifer sector	Average climate	68.82	303.50	3.74	2.12	0.00	3.00	63.32	36.89	118.45	2.28	129.07	39.39
	Drought		242.19	3.00	2.49	0.00	3.00	50.79	32.42	106.80	1.25	93.22	28.45
Windward aquifer sector	Average climate	124.35	484.94	2.26	21.32	0.60	3.49	80.50	57.89	253.10	7.57	175.56	29.65
	Drought		358.04	1.79	24.89	0.60	3.49	57.45	49.22	224.17	3.68	109.09	18.43

Table 8. Mean annual water-budget components from this study for average climate and drought conditions and components from the Water Resources Protection Plan (State of Hawai‘i, 1990; 2008) for aquifer-system areas on the Island of O‘ahu, Hawai‘i.

[See fig. 1 for locations of aquifer systems. Mgal/d, million gallons per day; Irr, irrigation; Septic, septic-system leachate; Direct rech, direct recharge; Canopy evap, forest canopy evaporation; Total ET, total evapotranspiration, which includes forest-canopy evaporation. n/a, not accounted for or not reported. WRPP, Water Resources Protection Plan (State of Hawai‘i, 1990; 2008). Water-budget-area descriptions: A, entire aquifer-system area; B, entire aquifer-system area excluding areas seaward of the 0-ft elevation contour of the top of the volcanic-rock aquifer (see fig. 1); C, entire aquifer-system area excluding ‘Ewa caprock areas (see fig. 1); D, aquifer-system used in WRPP. Average climate conditions for this study are 1978–2007 rainfall and 2010 land cover. Drought conditions for this study are 1998–2002 rainfall and 2010 land cover. Natural conditions for WRPP are 1916–83 mean rainfall and a uniform, unirrigated land cover. All WRPP water-budget components are from the 1990 WRPP, except where noted. Components may not balance because of rounding and direct recharge from cesspools and reservoirs. The source of water for direct recharge may be from external sources, including groundwater and imported streamflow. Some recharge may discharge to streams as base flow. Recharge estimates from this study do not include spillover from other aquifer-system areas]

Aquifer sector	Aquifer system	Source of estimate	Water-budget-area description	Area, in square miles	Condition/ Scenario	Water-budget component, in Mgal/d									
						Rain	Fog	Irr	Septic	Direct rech	Runoff	Canopy evap	Total ET	Storm drain	Recharge
Honolulu	Pālolo	This study	A	10.10	Average climate	28.27	0.09	3.05	0.01	0.25	3.14	3.30	17.81	2.85	8.28
		This study	A	10.10	Drought	21.66	0.06	3.35	0.01	0.25	2.42	2.83	16.51	1.73	5.12
		This study	B	5.36	Average climate	21.31	0.09	0.75	0.01	0.07	2.70	3.25	11.07	1.20	7.24
		This study	B	5.36	Drought	16.62	0.06	0.84	0.01	0.07	2.10	2.80	10.24	0.79	4.46
		WRPP	D	4.43	Natural	17.29	n/a	n/a	n/a	n/a	3.37	n/a	8.44	n/a	6
	Nu‘uanu	This study	A	14.79	Average climate	55.82	0.24	1.86	0.02	0.79	8.21	7.80	29.13	2.71	18.62
		This study	A	14.79	Drought	44.94	0.18	2.05	0.02	0.79	6.64	6.91	27.04	1.61	12.73
		This study	B	9.72	Average climate	47.53	0.24	0.41	0.02	0.64	7.57	7.75	22.31	0.87	17.85
		This study	B	9.72	Drought	38.88	0.18	0.48	0.02	0.64	6.17	6.88	20.87	0.63	12.33
		WRPP	D	8.62	Natural	41.45	n/a	n/a	n/a	n/a	10.26	n/a	16.42	n/a	20
	Kalihi	This study	A	9.83	Average climate	34.94	0.07	1.57	0.00	0.19	4.88	5.44	18.85	2.54	10.57
		This study	A	9.83	Drought	27.63	0.05	1.80	0.00	0.19	3.50	4.79	17.52	1.49	7.23
		This study	B	6.57	Average climate	28.87	0.07	0.64	0.00	0.06	4.31	5.43	14.49	0.78	10.04
		This study	B	6.57	Drought	23.22	0.05	0.75	0.00	0.06	3.11	4.78	13.55	0.52	6.88
		WRPP	D	6.33	Natural	27.12	n/a	n/a	n/a	n/a	6.03	n/a	12.05	n/a	12
	Moanalua	This study	A	22.95	Average climate	63.16	0.19	5.91	0.00	0.50	7.25	9.40	38.64	4.03	20.79
		This study	A	22.95	Drought	47.49	0.14	6.54	0.00	0.50	5.28	8.14	34.82	2.04	13.65
		This study	B	10.89	Average climate	46.68	0.19	0.79	0.00	0.01	6.23	9.29	22.84	0.53	18.05
		This study	B	10.89	Drought	36.73	0.14	0.90	0.00	0.01	4.62	8.06	20.75	0.34	12.04
		WRPP	D	10.92	Natural	41.07	n/a	n/a	n/a	n/a	4.68	n/a	20.80	n/a	24
	Wai‘alae-West	This study	A	7.30	Average climate	18.84	0.07	2.01	0.01	0.20	1.88	3.77	12.61	1.10	5.56
		This study	A	7.30	Drought	13.33	0.05	2.23	0.01	0.20	1.32	3.04	11.22	0.57	2.74
		This study	B	4.73	Average climate	15.45	0.07	0.48	0.00	0.03	1.69	3.66	9.04	0.44	4.85
		This study	B	4.73	Drought	11.08	0.05	0.54	0.00	0.03	1.20	2.96	7.94	0.25	2.31
	Wai‘alae-East	This study	A	20.02	Average climate	39.58	0.08	5.57	0.00	0.18	3.22	6.81	30.25	2.34	9.80
		This study	A	20.02	Drought	24.10	0.05	6.34	0.00	0.18	1.92	4.87	24.82	0.94	3.31
		This study	B	14.17	Average climate	31.31	0.08	2.07	0.00	0.12	2.71	6.44	21.53	1.23	8.11
		This study	B	14.17	Drought	19.35	0.05	2.37	0.00	0.12	1.64	4.63	17.30	0.52	2.50

Table 8.—Continued

Aquifer sector	Aquifer system	Source of estimate	Water-budget-area description	Area, in square miles	Condition/ Scenario	Water-budget component, in Mgal/d									
						Rain	Fog	Irr	Septic	Direct rech	Runoff	Canopy evap	Total ET	Storm drain	Recharge
Honolulu	Wai‘alae-West and Wai‘alae-East combined	This study	A	27.32	Average climate	58.42	0.15	7.58	0.01	0.38	5.10	10.58	42.86	3.44	15.36
		This study	A	27.32	Drought	37.43	0.10	8.57	0.01	0.38	3.24	7.91	36.04	1.51	6.05
		This study	B	18.89	Average climate	46.76	0.15	2.55	0.00	0.15	4.40	10.10	30.57	1.67	12.96
		This study	B	18.89	Drought	30.43	0.10	2.91	0.00	0.15	2.84	7.59	25.24	0.77	4.81
		WRPP	D	18.77	Natural	44.68	n/a	n/a	n/a	n/a	4.47	n/a	33.06	n/a	6, 8[a]
Pearl Harbor	Waimalu	This study	A	38.20	Average climate	153.27	0.86	5.33	0.01	0.13	22.81	23.53	70.16	4.06	62.81
		This study	A	38.20	Drought	118.90	0.66	5.91	0.01	0.13	14.93	20.47	64.03	2.04	44.85
		This study	B	31.48	Average climate	144.38	0.86	3.08	0.01	0.10	22.24	23.45	62.25	2.04	61.86
		This study	B	31.48	Drought	113.15	0.66	3.46	0.01	0.10	14.56	20.42	57.02	1.14	44.56
		WRPP	D	32.10	Natural	136.02	n/a	n/a	n/a	n/a	19.87	n/a	61.13	n/a	63
	Waipahu-Waiawa	This study	A	82.92	Average climate	231.64	1.11	38.86	0.02	4.25	33.01	26.43	141.02	6.97	96.60
		This study	A	82.92	Drought	176.41	0.91	43.32	0.02	4.25	22.42	22.96	129.28	3.39	72.09
		This study	B	60.47	Average climate	207.88	1.11	21.38	0.01	2.97	32.07	24.34	108.70	4.84	87.99
		This study	B	60.47	Drought	163.04	0.91	24.11	0.01	2.97	21.92	21.66	100.38	2.52	66.75
		This study	C	66.59	Average climate	214.75	1.11	22.70	0.00	3.05	32.36	24.90	115.14	5.62	89.26
		This study	C	66.59	Drought	167.12	0.91	25.55	0.00	3.05	22.08	22.02	105.62	2.86	67.23
		WRPP	D	60.72	Natural	215.97	n/a	n/a	n/a	n/a	28.65	n/a	102.15	n/a	143, 139[a], 77[b]
	‘Ewa-Kunia	This study	A	38.64	Average climate	55.08	0.26	9.64	0.01	1.29	2.97	6.53	47.20	2.25	14.69
		This study	A	38.64	Drought	32.60	0.15	10.66	0.01	1.29	1.69	4.36	38.32	0.92	5.10
		This study	B	26.12	Average climate	42.25	0.26	5.21	0.00	0.91	2.47	5.13	34.81	0.61	10.87
		This study	B	26.12	Drought	25.46	0.15	5.83	0.00	0.91	1.43	3.51	27.87	0.26	3.30
		This study	C	26.42	Average climate	42.56	0.26	5.28	0.00	0.91	2.48	5.16	35.04	0.65	10.98
		This study	C	26.42	Drought	25.65	0.15	5.90	0.00	0.91	1.43	3.52	28.02	0.28	3.38
	Makaīwa	This study	A	3.07	Average climate	4.09	0.00	0.60	0.00	0.01	0.21	0.21	3.07	0.10	1.44
		This study	A	3.07	Drought	2.44	0.00	0.65	0.00	0.01	0.12	0.14	2.56	0.04	0.53
		This study	B	2.31	Average climate	3.23	0.00	0.09	0.00	0.01	0.17	0.20	2.04	0.02	1.11
		This study	B	2.31	Drought	1.93	0.00	0.10	0.00	0.01	0.10	0.13	1.61	0.01	0.35
		This study	C	2.78	Average climate	3.78	0.00	0.50	0.00	0.01	0.20	0.20	2.70	0.09	1.33
		This study	C	2.78	Drought	2.26	0.00	0.54	0.00	0.01	0.11	0.14	2.23	0.03	0.48
	‘Ewa-Kunia and Makaīwa combined	This study	A	41.71	Average climate	59.17	0.26	10.24	0.01	1.30	3.18	6.74	50.27	2.35	16.13
		This study	A	41.71	Drought	35.04	0.15	11.31	0.01	1.30	1.81	4.50	40.88	0.96	5.63
		This study	B	28.43	Average climate	45.48	0.26	5.30	0.00	0.92	2.64	5.33	36.85	0.63	11.98
		This study	B	28.43	Drought	27.39	0.15	5.93	0.00	0.92	1.53	3.64	29.48	0.27	3.65
		This study	C	29.20	Average climate	46.34	0.26	5.78	0.00	0.92	2.68	5.36	37.74	0.74	12.31
		This study	C	29.20	Drought	27.91	0.15	6.44	0.00	0.92	1.54	3.66	30.25	0.31	3.86
		WRPP	D	28.10	Natural	46.10	n/a	n/a	n/a	n/a	3.11	n/a	33.68	n/a	22, 21[a], 7[b]

Table 8.—Continued

Aquifer sector	Aquifer system	Source of estimate	Water-budget-area description	Area, in square miles	Condition/ Scenario	Water-budget component, in Mgal/d									
						Rain	Fog	Irr	Septic	Direct rech	Runoff	Canopy evap	Total ET	Storm drain	Recharge
Wai‘anae	Nānākuli	This study	A	5.42	Average climate	9.29	0.05	0.35	0.01	0.08	0.58	1.09	6.04	0.13	3.02
		This study	A	5.42	Drought	5.75	0.03	0.38	0.01	0.08	0.34	0.75	4.82	0.06	1.06
		This study	B	4.59	Average climate	8.22	0.05	0.09	0.00	0.01	0.53	1.05	5.12	0.04	2.69
		This study	B	4.59	Drought	5.10	0.03	0.10	0.00	0.01	0.31	0.72	4.04	0.02	0.91
		WRPP	D	4.67	Natural	6.89	n/a	n/a	n/a	n/a	0.22	n/a	5.11	n/a	2
	Lualualei	This study	A	23.97	Average climate	37.22	0.13	2.51	0.07	0.33	2.22	4.41	26.77	0.65	10.80
		This study	A	23.97	Drought	22.56	0.07	2.72	0.07	0.33	1.28	2.98	21.24	0.30	3.33
		This study	B	15.30	Average climate	27.32	0.13	0.36	0.02	0.06	1.74	3.94	17.77	0.09	8.29
		This study	B	15.30	Drought	16.66	0.07	0.40	0.02	0.06	1.01	2.67	13.76	0.04	2.52
		WRPP	D	13.86	Natural	23.76	n/a	n/a	n/a	n/a	1.32	n/a	17.82	n/a	5
	Wai‘anae	This study	A	9.35	Average climate	18.14	0.21	1.15	0.04	0.27	1.44	2.13	11.12	0.27	7.09
		This study	A	9.35	Drought	10.90	0.11	1.22	0.04	0.27	0.83	1.47	9.00	0.12	2.79
		This study	B	7.61	Average climate	16.23	0.21	0.64	0.03	0.17	1.35	2.06	9.44	0.09	6.43
		This study	B	7.61	Drought	9.79	0.11	0.67	0.03	0.17	0.77	1.43	7.54	0.04	2.50
		WRPP	D	7.66	Natural	13.86	n/a	n/a	n/a	n/a	0.73	n/a	10.21	n/a	3
	Mākaha	This study	A	9.50	Average climate	20.85	0.29	2.17	0.05	0.18	1.83	2.79	13.06	0.11	8.57
		This study	A	9.50	Drought	12.72	0.16	2.44	0.05	0.18	0.87	1.95	10.99	0.05	3.70
		This study	B	7.77	Average climate	18.76	0.29	1.07	0.00	0.04	1.71	2.73	10.87	0.02	7.58
		This study	B	7.77	Drought	11.48	0.16	1.21	0.00	0.04	0.80	1.92	9.03	0.01	3.10
		WRPP	D	8.09	Natural	15.79	n/a	n/a	n/a	n/a	0.77	n/a	11.94	n/a	4
	Kea‘au	This study	A	12.67	Average climate	25.91	0.11	0.01	0.00	0.01	2.02	2.83	16.21	0.00	7.79
		This study	A	12.67	Drought	15.97	0.06	0.01	0.00	0.01	1.20	1.97	12.64	0.00	2.30
		This study	B	11.42	Average climate	23.95	0.11	0.00	0.00	0.01	1.89	2.78	14.83	0.00	7.34
		This study	B	11.42	Drought	14.76	0.06	0.00	0.00	0.01	1.12	1.93	11.59	0.00	2.20
		WRPP	D	11.33	Natural	21.04	n/a	n/a	n/a	n/a	1.08	n/a	15.64	n/a	5
North	Mokulē‘ia	This study	A	34.89	Average climate	73.69	0.85	3.30	0.07	0.74	5.97	11.96	51.64	0.00	21.60
		This study	A	34.89	Drought	44.95	0.46	3.81	0.07	0.74	3.45	8.46	41.01	0.00	6.72
		This study	B	27.49	Average climate	61.73	0.85	0.15	0.00	0.14	5.19	11.49	39.99	0.00	17.69
		This study	B	27.49	Drought	37.76	0.46	0.18	0.00	0.14	3.01	8.14	30.84	0.00	5.06
		WRPP	D	33.22	Natural	72.75	n/a	n/a	n/a	n/a	4.74	n/a	53.77	n/a	16
	Waialua	This study	A	21.40	Average climate	40.65	0.00	6.08	0.14	3.40	3.58	3.17	34.19	0.00	13.45
		This study	A	21.40	Drought	28.94	0.00	6.88	0.14	3.40	2.54	2.67	30.35	0.00	7.82
		This study	B	18.36	Average climate	36.12	0.00	3.21	0.01	2.63	3.32	3.03	28.24	0.00	11.02
		This study	B	18.36	Drought	26.07	0.00	3.73	0.01	2.63	2.38	2.57	24.87	0.00	6.12
		WRPP	D	17.19	Natural	36.83	n/a	n/a	n/a	n/a	2.46	n/a	27.01	n/a	8, 49[a], 8[b]

Table 8.—Continued

Aquifer sector	Aquifer system	Source of estimate	Water-budget-area description	Area, in square miles	Condition/ Scenario	Water-budget component, in Mgal/d									
						Rain	Fog	Irr	Septic	Direct rech	Runoff	Canopy evap	Total ET	Storm drain	Recharge
North	Kawailoa	This study	A	37.65	Average climate	122.47	0.02	1.34	0.26	1.42	15.73	21.52	76.12	0.00	34.10
		This study	A	37.65	Drought	95.06	0.01	1.52	0.26	1.42	11.49	18.54	67.63	0.00	19.96
		This study	B	35.19	Average climate	117.68	0.02	0.86	0.13	0.97	15.38	21.21	71.62	0.00	32.92
		This study	B	35.19	Drought	91.60	0.01	0.98	0.13	0.97	11.24	18.30	63.77	0.00	19.25
		WRPP	D	35.69	Natural	144.43	n/a	n/a	n/a	n/a	20.39	n/a	67.97	n/a	56
Central	Wahiawā	This study	A	68.82	Average climate	303.50	3.74	2.12	0.00	3.00	63.32	36.89	118.45	2.28	129.07
		This study	A	68.82	Drought	242.19	3.00	2.49	0.00	3.00	50.79	32.42	106.80	1.25	93.22
		WRPP	D	68.87	Natural	327.89	n/a	n/a	n/a	n/a	59.02	n/a	131.16	n/a	138
Windward	Ko‘olauloa	This study	A	41.19	Average climate	173.89	1.46	8.42	0.19	1.00	21.04	21.75	88.35	0.00	76.24
		This study	A	41.19	Drought	130.86	1.16	9.76	0.19	1.00	15.16	18.59	79.80	0.00	48.80
		This study	B	30.56	Average climate	148.19	1.46	0.84	0.01	0.09	17.50	20.15	63.94	0.00	69.12
		This study	B	30.56	Drought	113.10	1.16	0.99	0.01	0.09	12.76	17.35	57.55	0.00	44.93
		WRPP	D	32.57	Natural	165.92	n/a	n/a	n/a	n/a	32.56	n/a	62.02	n/a	71
	Kahana	This study	A	18.45	Average climate	101.88	0.24	0.29	0.09	0.24	21.38	11.62	38.57	0.00	43.24
		This study	A	18.45	Drought	80.08	0.20	0.32	0.09	0.24	15.91	10.29	35.17	0.00	30.48
		This study	B	16.40	Average climate	95.74	0.24	0.05	0.01	0.05	20.18	11.17	33.74	0.00	42.13
		This study	B	16.40	Drought	75.60	0.20	0.05	0.01	0.05	15.06	9.92	30.89	0.00	29.92
		WRPP	D	16.24	Natural	109.02	n/a	n/a	n/a	n/a	49.48	n/a	30.93	n/a	29
	Ko‘olaupoko	This study	A	29.71	Average climate	125.51	0.45	3.14	0.19	1.11	23.83	15.19	64.33	3.24	39.08
		This study	A	29.71	Drought	92.63	0.35	3.91	0.19	1.11	17.40	13.12	57.09	1.73	22.31
		This study	B	26.58	Average climate	116.22	0.45	2.38	0.11	0.87	22.15	14.85	57.82	2.61	37.45
		This study	B	26.58	Drought	86.13	0.35	3.03	0.11	0.87	16.25	12.85	51.55	1.40	21.49
		WRPP	D	27.22	Natural	125.71	n/a	n/a	n/a	n/a	33.69	n/a	51.84	n/a	40
	Waimānalo	This study	A	35.00	Average climate	83.66	0.11	9.47	0.13	1.14	14.25	9.33	61.85	4.33	17.00
		This study	A	35.00	Drought	54.47	0.08	10.90	0.13	1.14	8.98	7.22	52.11	1.95	7.50
		This study	B	18.81	Average climate	52.95	0.11	2.41	0.04	0.22	9.25	8.43	33.18	1.16	12.11
		This study	B	18.81	Drought	35.29	0.08	2.83	0.04	0.22	5.99	6.58	27.09	0.54	5.00
		WRPP	D	19.60	Natural	64.39	n/a	n/a	n/a	n/a	10.26	n/a	37.33	n/a	17, 13[a]

[a]Updated value used in the 2008 WRPP (Roy Hardy, CWRM, written commun., May 2014).

[b]Updated value used in the 2008 WRPP (Roy Hardy, CWRM, written commun., May 2014) with spillover removed.

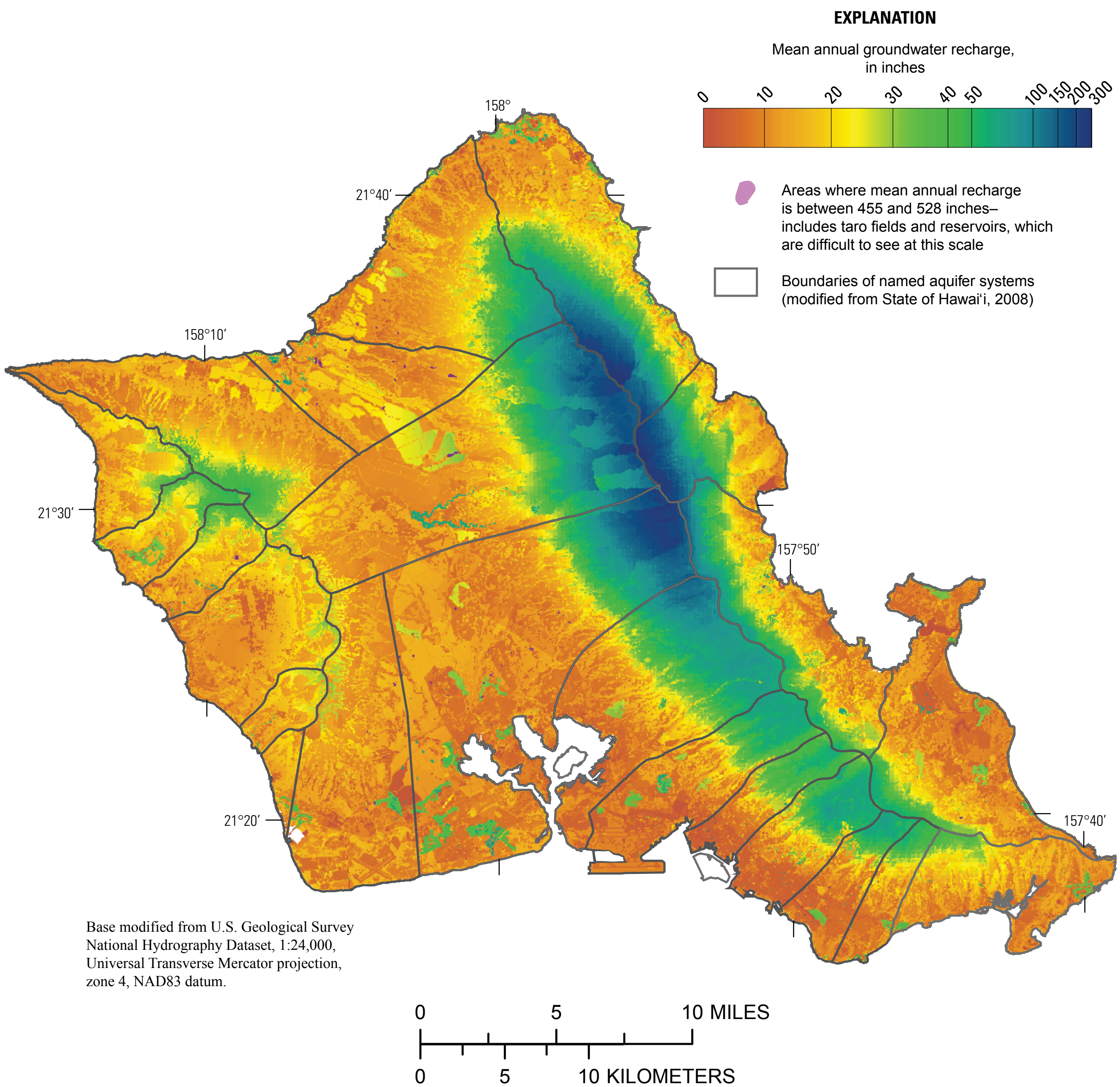

Figure 10. The distribution of mean annual recharge for average climate conditions (1978–2007), calculated using the water-budget model, Island of Oʻahu, Hawaiʻi.

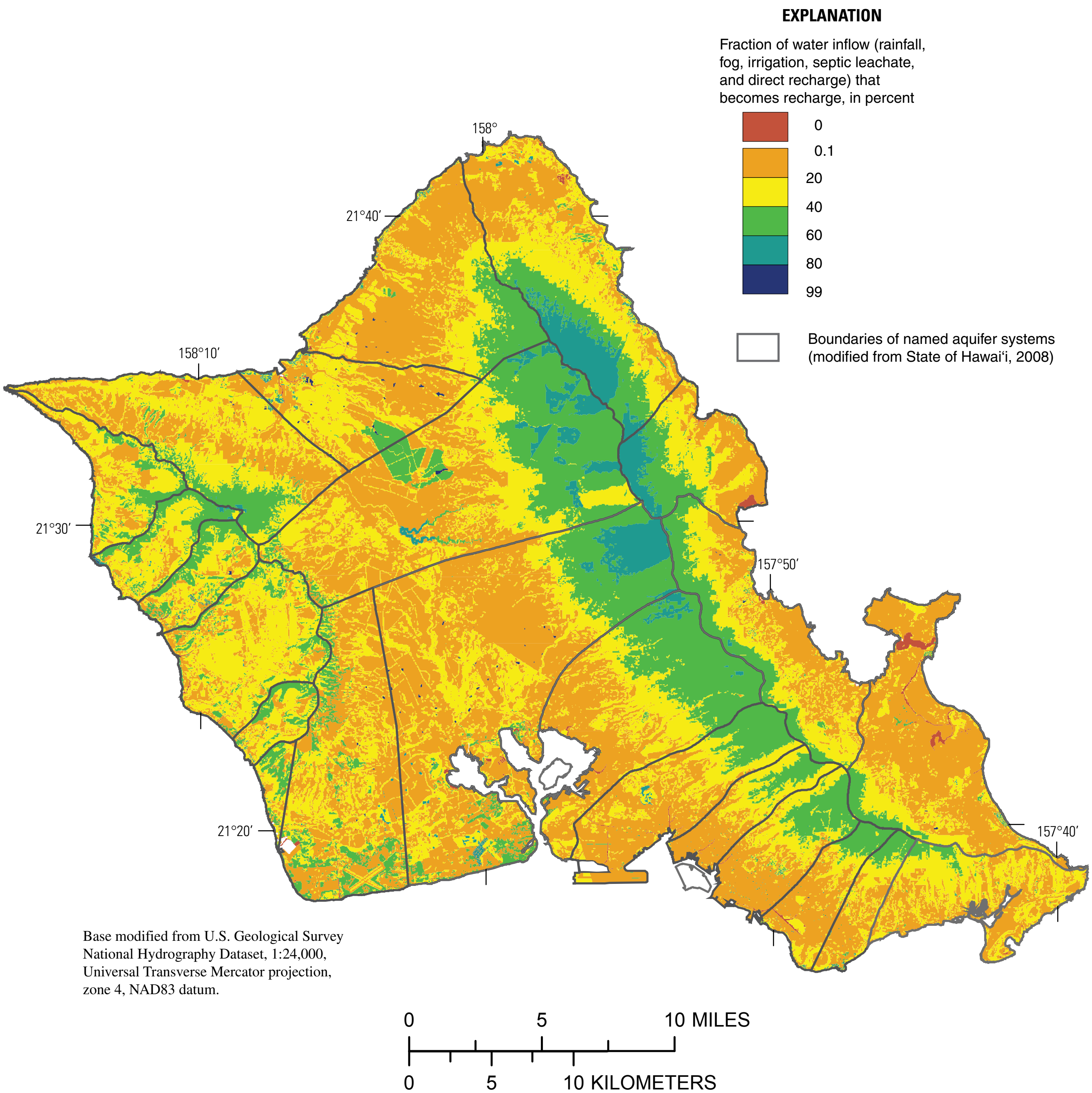

Figure 11. Estimated fraction of total water inflow that becomes groundwater recharge in the water-budget simulation for average climate conditions on the Island of O‘ahu, Hawai‘i.

(Roy Hardy, written commun., May 2014). These allocations, termed spillover in the 2008 WRPP, are included in the recharge estimate for each of these systems in the 2008 WRPP. For purposes of comparison, spillover is subtracted from the WRPP-recharge estimates in table 8.

As shown on table 8, water-budget-area description B approximates the areas given in the WRPP fairly well for most aquifer systems. Overall water-budget area is about 466 mi^2 in the WRPP and about 461 mi^2 for water-budget-area description B in this study. Owing to this, the remainder of this section will compare recharge estimates from the WRPP with recharge estimates from this study for water-budget-area description B, except for the Wahiawā aquifer system, which will be compared using water-budget-area description A because no caprock occurs in this area.

Island-wide, the recharge estimate in this study for average climate conditions, 612 Mgal/d for water-budget area B, is very close to the WRPP recharge estimate of 608 Mgal/d. However, differences in recharge estimates are substantial for some aquifer systems. Recharge estimates from this study are higher than estimates in the WRPP for 12 of the 21 aquifer systems compared (includes recombined aquifer systems; table 8). Small area inconsistencies aside, the reasons for differences in the recharge estimates are related to methods and datasets used to estimate individual water-budget components (table 9). The 1990 WRPP states that ET was estimated as (1) 40 in/yr for areas where mean rainfall was at least 55 in/yr, and (2) 73 percent of rainfall for areas where mean rainfall was less than 55 in/yr. In this study, ET is calculated daily on the basis of available mean monthly potential ET, soil moisture, vegetative cover, and soil type. The runoff-rainfall relations used to estimate runoff in the WRPP were developed from streamflow measurements without subtracting base flow. In contrast, base flow was subtracted from streamflow measurements when developing the runoff-rainfall relations for this study. Fog interception is included in this study, but not in the WRPP. Rainfall estimates of the WRPP are based on 1916–83 mean isohyets (Giambelluca and others, 1986), whereas estimates of this study are based on 1978–2007 monthly rainfall maps (Frazier and others, 2016). Different spatial extrapolation techniques were used to prepare these two rainfall datasets; therefore, the difference in the rainfall values for any given area may not be attributable only to the different periods of record. Additionally, the WRPP did not account for septic leachate, irrigation, and direct recharge from reservoirs, cesspools, and water-main leaks.

The recharge estimates of this study are substantially higher than estimates of the WRPP for the aquifer systems in the Waiʻanae aquifer sector, including Keaʻau, Mākaha, Waiʻanae, Lualualei, and Nānākuli (table 8). Estimates from this study are 35 to 114 percent higher than the WRPP estimates for these aquifer systems. The primary reason for the higher recharge estimates is the substantially higher rainfall in the Frazier and others (2016) monthly rainfall maps compared to Giambelluca and others (1986). The recharge estimate from this study is

Table 9. Important differences between the recharge-estimation methods used in this study and the recharge-estimation methods used in the Water Resources Protection Plan (State of Hawaiʻi, 1990)

[WRPP, Water Resources Protection Plan (State of Hawaiʻi, 1990)]

Factor	This study	WRPP	Effect on amount of recharge estimated in this study relative to the WRPP recharge estimate[1]
Time step	Daily	Annual	More
Irrigation	Included	Not included	More
Fog interception	Included	Not included	More
Septic-system leachate	Included	Not included	More
Direct recharge[2]	Included	Not included	More
Storm-drain capture	Included	Not included	Less
Direct runoff	Estimated as the difference between streamflow and base flow	Estimated as being equal to streamflow (without subtracting base flow	More
Total evapotranspiration (ET)	Estimated using potential ET, soil moisture, and land-cover and soil properties; canopy-evaporation is separately estimated and included for forests	Estimated on the basis of mean annual rainfall; canopy evaporation is not separately estimated	Indeterminate (depends on area being considered)
Rainfall	1978–2007 monthly rainfall (Frazier and others, 2016)	1916–1983 mean annual rainfall (Giambelluca and others, 1986)	Indeterminate (depends on area being considered)
Excluded parts of aquifer systems[3]	Defined	Not explicitly defined	Indeterminate (excluded areas not explicitly defined in the WRPP)

[1]All other factors being equal.

[2]Includes water-main leakage and seepage from cesspools, reservoirs, and other water bodies.

[3]Both studies assumed certain areas of aquifer systems, generally near the coast, did not contribute recharge to the volcanic-rock aquifer

also substantially higher for the combined Waiʻalae-East and Waiʻalae-West aquifer systems. Higher rainfall estimates in Frazier and others (2016), lower total ET, and lower runoff are responsible for the 62 percent higher recharge calculated in this study for these combined aquifer systems. For the Kahana aquifer system, in which this study estimates 45 percent more recharge than the WRPP, rainfall in Frazier and others (2016) is actually much lower than the WRPP estimate. However, runoff is more than twice as high in the WRPP versus this study, leading to a higher recharge estimate in this study. The recharge estimate of this study is 41 percent lower than the estimate of the WRPP for the Kawailoa aquifer system. Lower rainfall in the Frazier and others (2016) monthly rainfall maps is the primary reason for the lower recharge estimate. Removing spillover from the WRPP estimates of recharge for the Waialua, Waipahu-Waiawa, and combined ʻEwa-Kunia and Makaīwa aquifer systems, yields recharge estimates of 8, 77, and 7 Mgal/d, respectively (table 8). Recharge estimates from this study are 38, 14, and 71 percent higher, respectively, for these aquifer systems. The primary reason for the higher recharge estimates for these areas is the inclusion of irrigation, which is left out of the WRPP water budget.

Comparisons with Other Relevant Studies

Comparisons of recharge for average climate conditions estimated in this study are compared with estimates from Shade and Nichols (1996) for the mid-1980s (table 10). Because of the substantial changes in agricultural land use and associated irrigation practices that occurred in north-central and southern Oʻahu between the mid-1980s and 2010, comparisons for these areas were not deemed relevant. Estimated recharge for the Waiʻanae aquifer sector is about 16 percent higher in this study than in Shade and Nichols (1996). The primary reason for the difference is the inclusion of irrigation, mostly for developed land covers, in this study; Shade and Nichols (1996) did not include any irrigation. The sum of rainfall, total ET, and runoff is nearly equal in the two studies. Estimated recharge for the Windward aquifer sector is about 11 percent lower in this study than in Shade and Nichols (1996). The inclusion of irrigation in this study is not enough to compensate for the lower rainfall, about 10 percent, and higher ET, about 6 percent, compared with Shade and Nichols (1996). Estimated recharge for the combined Waiʻalae-East and Waiʻalae-West aquifer systems is 19 percent lower in this study than in Shade and Nichols (1996). Because the sum of rainfall, total ET, and runoff is nearly equal in the two studies, the difference in recharge can be attributed to the inclusion of storm-drain capture in this study. For the three locations compared in table 10, total ET in this study is always higher than Shade and Nichols (1996).

Because of their importance to the overall water budget, estimates of ET from this study are compared to the latest estimates from Giambelluca and others (2014). For the Island of Oʻahu, mean annual total ET for this study for average climate conditions is about 1,015 Mgal/d, which is 16 percent more than mean annual ET from Giambelluca and others (2014). Compared to ET estimates of Giambelluca and others (2014), the mean annual total ET estimates in this study are (1) about 13 percent higher for subareas mapped as grassland, (2) about 1 percent lower for subareas mapped as shrubland, (3) about 8 percent higher for subareas mapped as native forest, alien forest, or tree

Table 10. Comparison of water-budget components from this study with components from a previous study for various areas of the Island of Oʻahu, Hawaiʻi.

[See fig. 1 for locations of aquifer sectors and systems; Mgal/d, million gallons per day; Irr, irrigation; Septic, septic-system leachate; Direct rech, direct recharge; Canopy evap, forest canopy evaporation; Total ET, total evapotranspiration, which includes forest-canopy evaporation; Average climate conditions for this study are 1978–2007 rainfall and 2010 land cover; conditions for Shade and Nichols (1996) are 1916–83 rainfall and mid-1980s land cover; n/a, not accounted for or not reported. Components may not balance because of rounding and direct recharge from cesspools and reservoirs. The source of water for direct recharge may be from external sources, including groundwater and imported streamflow. Some recharge may discharge to streams as base flow]

Location	Source of estimate	Condition/ Scenario	Area, in square miles	Water-budget component, in Mgal/d									
				Rain	Fog	Irr	Septic	Direct rech	Runoff	Canopy evap	Total ET	Storm drain	Recharge
Waiʻanae Aquifer Sector	This study	Average climate	60.91	111.40	0.79	6.19	0.17	0.86	8.09	13.25	73.20	1.16	37.27
	Shade and Nichols (1996)	Mid-1980s	60.91	103	n/a	n/a	n/a	n/a	8	n/a	63	n/a	32
Windward Aquifer Sector	This study	Average climate	124.35	484.94	2.26	21.32	0.59	3.49	80.50	57.88	253.10	7.57	175.55
	Shade and Nichols (1996)	Mid-1980s	124.47	536	n/a	n/a	n/a	n/a	100	n/a	238	n/a	198
Waiʻalae-East and West Aquifer Systems	This study	Average climate	27.32	58.42	0.15	7.58	0.01	0.38	5.10	10.58	42.86	3.44	15.36
	Shade and Nichols (1996)	Mid-1980s	28.44	62	n/a	n/a	n/a	n/a	7	n/a	36	n/a	19

plantation, (4) about 33 percent higher for subareas mapped as developed, and (5) about 5 percent lower for subareas mapped as sparsely vegetated. ET estimates for forests were expected to be close because forest crop coefficients and canopy evaporation were calibrated to ET datasets of Giambelluca and others (2014). However, they were calibrated using data that included all forests on Kauaʻi and Maui, as well as Oʻahu. The differences in mean annual ET estimates may be related to differences in base periods, computational methods, and soil-moisture estimates. For example, in areas where ET estimates are much greater than those of Giambelluca and others (2014), the estimated amount of soil moisture available for ET may be greater than that estimated by Giambelluca and others (2014), allowing for a greater volume of ET with all other conditions being equal. On the other hand, in areas where ET estimates of the water budget are less than those of Giambelluca and others (2014), the estimated amount of soil moisture available for ET in the water-budget model may be less.

Recharge for Drought Conditions

To assess the impact of drought conditions on recharge, rainfall during 1998–2002 was selected to represent drought conditions on Oʻahu because this period had the lowest 5-yr mean rainfall during 1978–2007. Other than rainfall, all water-budget inputs used to calculate recharge for drought conditions were the same as those used for average climate conditions. Because the fog-to-rainfall ratios used for average climate conditions were also used for drought conditions, fog-interception rates for drought conditions were less than those for average climate conditions.

For the Island of Oʻahu, recharge for drought conditions is about 417 Mgal/d, which is about 37 percent lower than recharge for average climate conditions (table 7). Aquifer-system precipitation for drought conditions ranges from 20 to 41 percent lower than corresponding precipitation for average climate conditions (table 8). Aquifer-system recharge for drought conditions is about 25 to 70 percent lower than corresponding recharge for average climate conditions. The reduction in recharge for drought conditions, as a percentage (fig. 12), tends to be more pronounced in areas with lower mean rainfall. The reduction in recharge is directly related to the reduction in precipitation relative to average climate conditions, except in areas with inflows from irrigation, septic-system leachate, and direct recharge.

Sensitivity Analysis

Uncertainty exists in many of the water-budget inputs used in this study. The inputs used in the water-budget calculations were considered to be those most reasonable. To analyze the effect that uncertainty in water-budget inputs has on estimated recharge, the water-budget model was rerun, changing one input value at a time within a reasonable range. The parameters tested were (1) available water capacity, (2) fog interception-to-rainfall ratios, (3) root depth, (4) runoff-to-rainfall ratios, (5) crop coefficient, (6) canopy capacity, (7) ratio of mean evaporation rate to mean precipitation rate during saturated canopy conditions, V, and (8) storm-drain systems. For available water capacity, the high and low published values (USDA, 2006a) were tested. For fog interception-to-rainfall ratios and root depths, the “baseline” ratios and values, respectively, used in water-budget calculations for average climate and drought conditions were increased by 50 percent and decreased by 50 percent. Runoff-to-rainfall ratios were adjusted on the basis of bias and root-mean-square-error statistics (for Oʻahu) of the runoff regression models (table 5). For crop coefficients, baseline values were increased by 20 percent and decreased by 20 percent. Canopy-storage capacity values of 0.08 and 0.02, corresponding to an increase and decrease of 0.03 from the baseline value, were tested. Values for V were increased by 0.1 units and were decreased by 0.1 units. For the latter case, however, V was assumed to be no less than 0.01. A water-main leakage rate of 15 Mgal/d, equal to 10 percent of the average system flow rate, was tested. Finally, the effect of storm-drain collection in medium- and high-intensity developed land covers was tested by “turning off” storm drains, meaning that the excess water, W_i, that flows off the impervious fraction of a subarea flows to the pervious fraction of that subarea, instead of being collected in the storm drain.

The recharge estimates for the sensitivity analysis are compared with recharge estimates for average climate conditions for Mākaha, Waipahu-Waiawa, Nuʻuanu, Waimānalo, and Kawailoa aquifer systems (table 11). These five aquifer systems cover a range of climates and land covers on Oʻahu. The Mākaha aquifer system is representative of the drier, leeward side of the Waiʻanae Range. Its land cover is dominated by mostly alien forest and grassland. The Waipahu-Waiawa aquifer system is representative of south-central Oʻahu and the Pearl Harbor area. It encompasses a wide variety of land cover and climate conditions and is very important to the municipal water supply of the island. The Nuʻuanu aquifer is representative of southeast, leeward Oʻahu. The aquifer system extends from the urban center of Honolulu up to the crest of the Koʻolau Range. Its land cover is mostly high- to medium-intensity developed at lower elevations and alien and native forest at higher elevations; the rainfall gradient is steep. The Waimānalo aquifer system is representative of the windward side of the Koʻolau Range and encompasses a wide variety of land covers. The Kawailoa aquifer system is representative of the northern side of the island. Alien and native forest dominate the upper elevations, and the lower elevations are mostly grass and shrubland with some low-intensity development near the coast.

For the Mākaha aquifer system, the parameters with the largest effects on recharge are root depth and V. Both of these parameters are related to ET and demonstrate the importance of ET, especially canopy evaporation, in drier, forested areas.

For the Waipahu-Waiawa aquifer system, the parameter with the largest effect on recharge is V. Changes to all other parameters have small effects—less than 7 percent—on recharge. The wide variety of land cover and climate may be responsible for the relatively small changes to recharge.

For the Nuʻuanu aquifer system, three parameters have substantial effects on recharge: runoff-to-rainfall ratios, storm-drain capture, and V. In the wetter, forested uplands of this aquifer

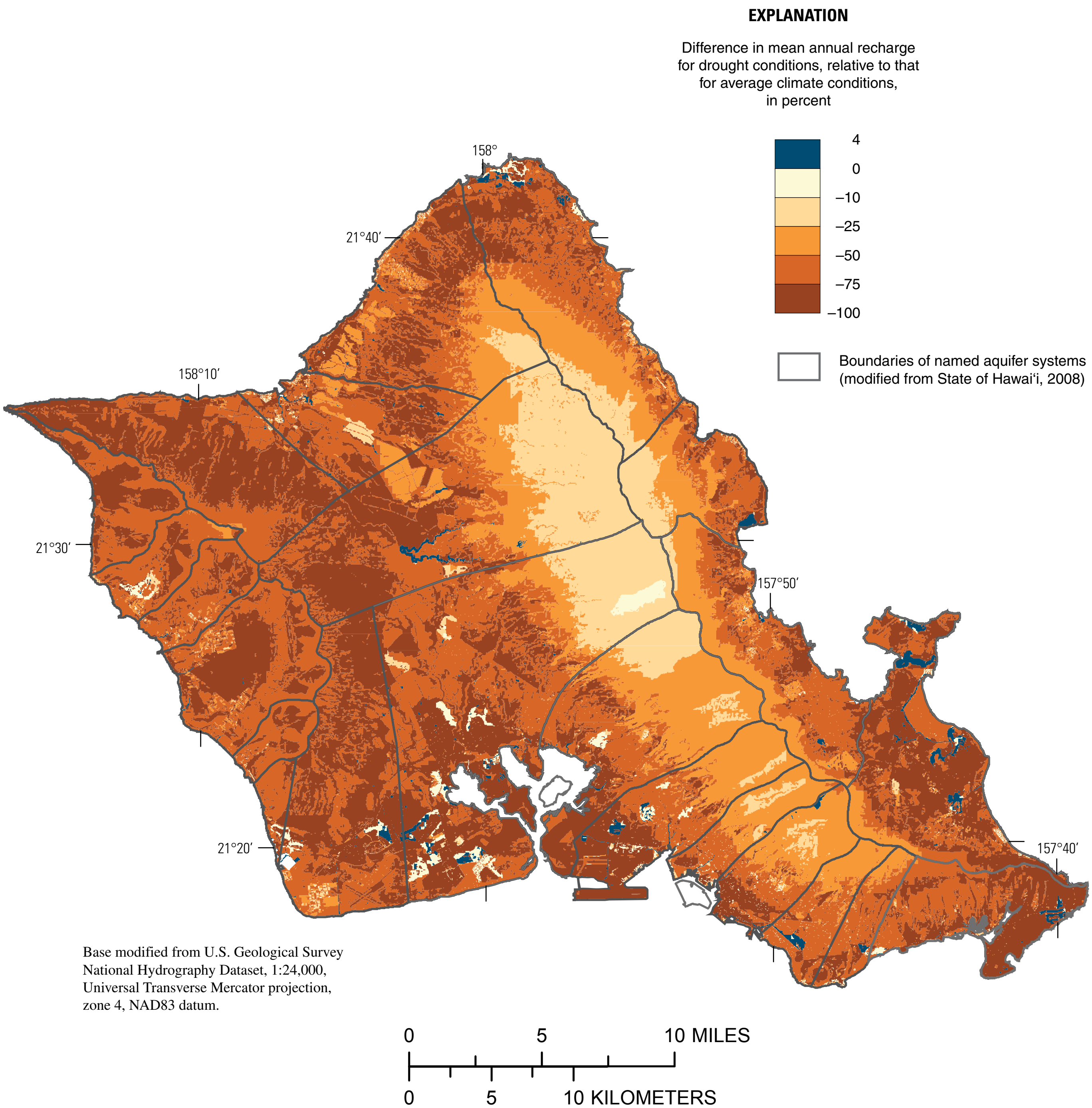

Figure 12. The percentage difference in mean annual recharge for drought conditions (1998–2002) relative to average climate conditions, calculated using the water-budget model, Island of O‘ahu, Hawai‘i.

Table 11. Results of sensitivity testing for selected water-budget parameters performed for selected aquifer systems on the Island of Oʻahu, Hawaiʻi.

[See fig.1 for locations of aquifer systems; baseline parameters are those used for average climate conditions; %, percent; RMSE, root mean square error of regional-runoff regression; see table 5 for RMSE and bias for Oʻahu]

Parameter	Adjusted parameter value	Percentage difference in recharge				
		Mākaha	Waipahu-Waiawa	Nuʻuanu	Waimānalo	Kawailoa
Available water capacity	Low reported value[1]	-2.3	-0.8	-0.9	-2.3	-1.2
	High reported value[1]	2.6	1.0	1.2	3.1	1.4
Fog interception-to-rainfall ratios	150% of baseline	1.3	0.5	0.5	0.3	0.0
	50% of baseline	-1.3	-0.5	-0.5	-0.3	0.0
Root depth	150% of baseline	-4.8	-2.8	-2.4	-8.5	-3.9
	50% of baseline	10.3	5.5	4.6	16.5	7.9
Runoff-to-rainfall ratios	Regression bias adjustment[2]	-0.1	0.1	0.3	12.6	-0.1
	Increase by regression RMSE[3]	-6.7	-4.3	-14.7	-27.5	-12.9
	Decrease by regression RMSE[3]	6.2	4.1	14.9	30.4	13.6
Crop coefficients	120% of baseline	-4.7	-3.9	-8.8	-7.6	-11.0
	80% of baseline	6.5	4.8	10.0	10.7	14.3
Canopy capacity	Increase by 0.03 units	-2.4	-4.7	-7.6	-5.4	-7.6
	Decrease by 0.03 units	1.8	3.3	5.8	4.4	5.9
Ratio of the mean evaporation rate to mean precipitation rate during saturated conditions, *V*	Increase by 0.1 units	-8.0	-12.9	-15.6	-11.9	-17.3
	Decrease by 0.1 units	8.3	8.4	13.7	11.9	17.4
Water-main leakage	Increase system leakage rate to 15 Mgal/d[4]	0.2	0.3	0.4	0.5	0.1
Storm-drain capture	off	1.2	6.5	13.3	23.2	0.0

[1]Low and high values reported in U.S. Department of Agriculture (2006a).

[2]For leeward areas, runoff-to-rainfall ratios were increased by 1.0 and decreased by 13.8 percent for the wet and dry seasons, respectively. For windward areas, runoff-to-rainfall ratios were decreased by 33.0 and 28.8 percent for the wet and dry seasons, respectively.

[3]For leeward areas, runoff-to-rainfall ratios were adjusted by 0.06 and 0.07 units for the wet and dry seasons, respectively. For windward areas, runoff-to-rainfall ratios were adjusted by 0.12 and 0.09 units for the wet and dry seasons, respectively.

[4]The value of 15 Mgal/d represents 10% of the average flow through the water system.

system, runoff and canopy evaporation are important to the water budget. In the lower, urban area, storm-drain capture is important.

For the Waimānalo aquifer system, four parameters have substantial effects on recharge: root depth, runoff-to-rainfall ratios, storm-drain capture, and *V*. The uncertainty in the runoff-to-rainfall ratio regression is higher on the windward side of the island than on the leeward side (table 5), resulting in a greater change in recharge compared to the other aquifer systems tested. The relatively large percentage of developed land cover is responsible for the considerable sensitivity to storm-drain capture.

For the Kawailoa aquifer system, three parameters have substantial effects on recharge: runoff-to-rainfall ratios, crop coefficients, and *V*. The large percentage of forest, nearly all of which lies outside of the fog zone, is responsible for the sensitivity to the canopy-evaporation parameter, *V*. Relatively high rainfall in the higher elevations leads to substantial sensitivity to runoff ratios.

Suggestions for Future Study and Additional Data Collection

Lack of data or sparse, uneven distribution of data in space and time, and poor understanding of some hydrologically relevant processes limit the accuracy of study results. This section discusses information that could advance future efforts to more accurately assess the distribution of groundwater recharge on Oʻahu.

Rainfall is an essential dataset for estimating recharge. Although Oʻahu has a higher number of rain gages per square mile than most other Hawaiian Islands, the placement of gages and their periods of operation have been dictated by the water-supply needs of humans—particularly agriculture (Giambelluca and others, 1986). Rain gages are scarce in areas that are less populated or unfavorable for agriculture, such as in the high-elevation interiors of islands or areas having rugged terrain. Estimates of rainfall for these areas thus have a greater degree of uncertainty (Giambelluca and others, 2013), yet these tend to be the wettest areas of the islands and the areas where most recharge occurs. Recharge estimates in areas can be improved with rainfall data from these sparsely gaged areas. The number of rain gages, however, has decreased sharply in the past 30 years, particularly as a result of the discontinuation of gage networks that were maintained by large sugarcane and pineapple plantations and associated irrigation companies (Giambelluca and others, 2013).

Fog-interception data are particularly scant. Fog interception provides a substantial part of the water available for groundwater recharge over large areas of the Hawaiian Islands, but has been quantified by only a few studies in a few places. As a result, fog-interception distribution was applied in a very generalized fashion in the recharge calculation. Recharge estimates can be improved with a better quantification of the spatial and temporal variability of fog-interception rates, and the ability of different types of vegetation to intercept fog.

An acknowledged limitation of the water-budget model is that monthly reference ET is uniformly distributed among each day of the month, regardless of the daily rainfall distribution over the month. In reality, reference ET should be lower during cloudy, rainy days than during sunny days. Recharge estimates could be improved with more measurements of the daily variations of reference ET across the study area.

Another ET-related limitation of this study is the current lack of data needed to more accurately differentiate ET parameters among native and alien species of plants. Replacement of native forest by invasive alien plants like strawberry guava (*Psidium cattleianum*) is a problem on O‘ahu. More data could be used to develop better crop coefficients for native and alien plants. These improvements would help to better estimate the difference in recharge that could be expected in native versus alien dominated forests.

The accuracy of the modified Gash canopy-interception model used in this study is limited by the quantity, quality, and spatial distribution of data used to develop model parameters. Field measurements of one parameter, the ratio of the mean evaporation rate to the mean precipitation rate during saturated canopy conditions (V), are especially lacking. Additional measurements of canopy-evaporation and related parameters could be used to better confirm and calibrate the canopy-evaporation estimates of the modified Gash model.

Runoff is perhaps the most uncertain parameter in the recharge analysis. The runoff-to-rainfall ratio method in the water-budget model in this study was improved by developing regression equations relating the ratio to drainage-basin characteristics, and using these equations to extrapolate the ratios from gaged to ungaged basins. However, because the number of ungaged basins was far greater than the number of gaged basins, ratios had to be extrapolated to some ungaged basins having characteristic values that were beyond the range of values used to develop the regression equations. Stream-gage data from more basins with a wider range of characteristic values are needed to improve the regression approach to regionalizing runoff-to-rainfall ratios.

The runoff-to-rainfall ratio method used in the water-budget model in this study was also improved by varying the ratios on a seasonal basis with rainfall. Concurrent daily direct runoff and high-resolution rainfall data could improve the understanding of the processes controlling temporal variability in runoff estimates. Results of the regional-regression analysis suggest that runoff in windward and leeward basins differ statistically. Better understanding of the physical basis of this statistical difference would improve conceptualization of runoff processes.

The water-budget model used in this study applies the runoff-to-rainfall ratios at the catchment-zone level, that is, ratios do not vary spatially within a catchment zone, even though the catchment zone may encompass a variety of land covers, soil types, slopes, and a range of climates. The catchment-zone-level application of runoff-to-rainfall ratios limits the ability of the model to assess differences in runoff and groundwater recharge that may exist between different areas within the catchment zone, such as between forested and deforested areas. Part of the limitation stems from the scarcity of studies assessing the variation in runoff rates for different vegetation, soil, and slope characteristics in Hawai‘i. In a study comparing adjacent deforested rangeland and reforested areas on the south slope of Haleakalā, Maui, Perkins and others (2012; 2014) found that the reforested areas had soil hydraulic properties that favored rapid and deep infiltration of water. This finding suggests that runoff would be lower from the forested area than from the deforested area of their study, but the study did not measure runoff. Better understanding of the processes and distribution of hydrogeological characteristics at the catchment-zone scale are important for answering questions that are often posed about watershed management, such as the effect of forest restoration on water resources.

Summary and Conclusions

The main objective of this study was to determine the spatial distribution of mean annual groundwater recharge for the Island of O‘ahu. Recharge was calculated with a water-budget model that used a daily computational interval to simulate the hydrological processes and physical conditions that affect recharge. Hydrological processes and physical conditions on O‘ahu were defined using the most current datasets available—including maps of 2010 land cover, 1978–2007 monthly rainfall, and mean monthly reference ET. Monthly rainfall was disaggregated into daily rainfall using the method of fragments and daily rainfall records from 47 rain gages. The water-budget model and the most current datasets available were used to estimate the spatial distribution of mean annual groundwater recharge for two scenarios, (1) average climate conditions, based on 2010 land cover and rainfall during 1978–2007, and (2) drought conditions, based on 2010 land cover and rainfall during 1998–2002.

For the Island of O‘ahu, mean annual recharge is about 660 Mgal/d for average climate conditions. Expressed as a uniform depth over the entire area of the island, recharge for average climate conditions is about 23.3 in/yr. Recharge is about 36 percent of precipitation (sum of rainfall and fog interception) and is about 34 percent of total inflow (sum of precipitation, irrigation, septic-system leachate, and direct recharge). Recharge is high along the crest of the Koʻolau Range, reaching as much as about 180 in/yr in the north-central part of the range. Relatively high recharge rates also occur in the higher elevations of the Waiʻanae Range, reaching as much as about 60 in/yr near the summit of Mt. Kaʻala. Recharge is much lower outside of the mountainous areas of the island. In undeveloped and nonagricultural areas at low elevation, recharge is commonly less than 5 in/yr. In general, areas that have water inflows from irrigation, septic-system leaching, and direct recharge have more recharge than nearby areas without these supplemental water inflows.

On the basis of assumptions made regarding caprock areas and the spillover of high-level recharge in the 2008 WRPP, the island-wide estimate of groundwater recharge for average climate conditions from this study is within 1 percent of the recharge estimate used in the 2008 WRPP. Recharge estimates from this study are higher for 12 of the aquifer-system areas and lower for 9. Differences in mean rainfall distribution and the inclusion of irrigation in this study are the primary reasons for differences in recharge estimates between this study and the 2008 WRPP. Compared to ET estimates of Giambelluca and others (2014), ET estimates of this study are about 16 percent higher island-wide. This difference is largely attributable to higher ET estimates for developed and grassland land covers in this study, which are about 33 and 13 percent higher, respectively.

Mean annual recharge on Oʻahu for drought conditions is about 417 Mgal/d, which is about 37 percent lower than recharge for average climate conditions. Expressed as a uniform depth over the entire area of the island, recharge for drought conditions is about 14.7 in/yr. Aquifer-system precipitation for drought conditions ranges from 20 to 41 percent less than corresponding precipitation for average climate conditions. Aquifer-system recharge for drought conditions ranges from 25 to 70 percent lower than corresponding recharge for average climate conditions.

The spatial distribution of rainfall is the primary factor determining the spatial distribution of recharge for most areas on Oʻahu. In forested areas, recharge estimates are also sensitive to forest-canopy evaporation. In drier areas, recharge estimates are more sensitive to parameters that are related to ET, such as root depths and crop coefficients, whereas in wetter areas, recharge estimates are more sensitive to runoff-to-rainfall ratios. Additional collection and analysis of precipitation, ET, runoff, and soils data are necessary to better understand the hydrological processes that affect recharge across Oʻahu.

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