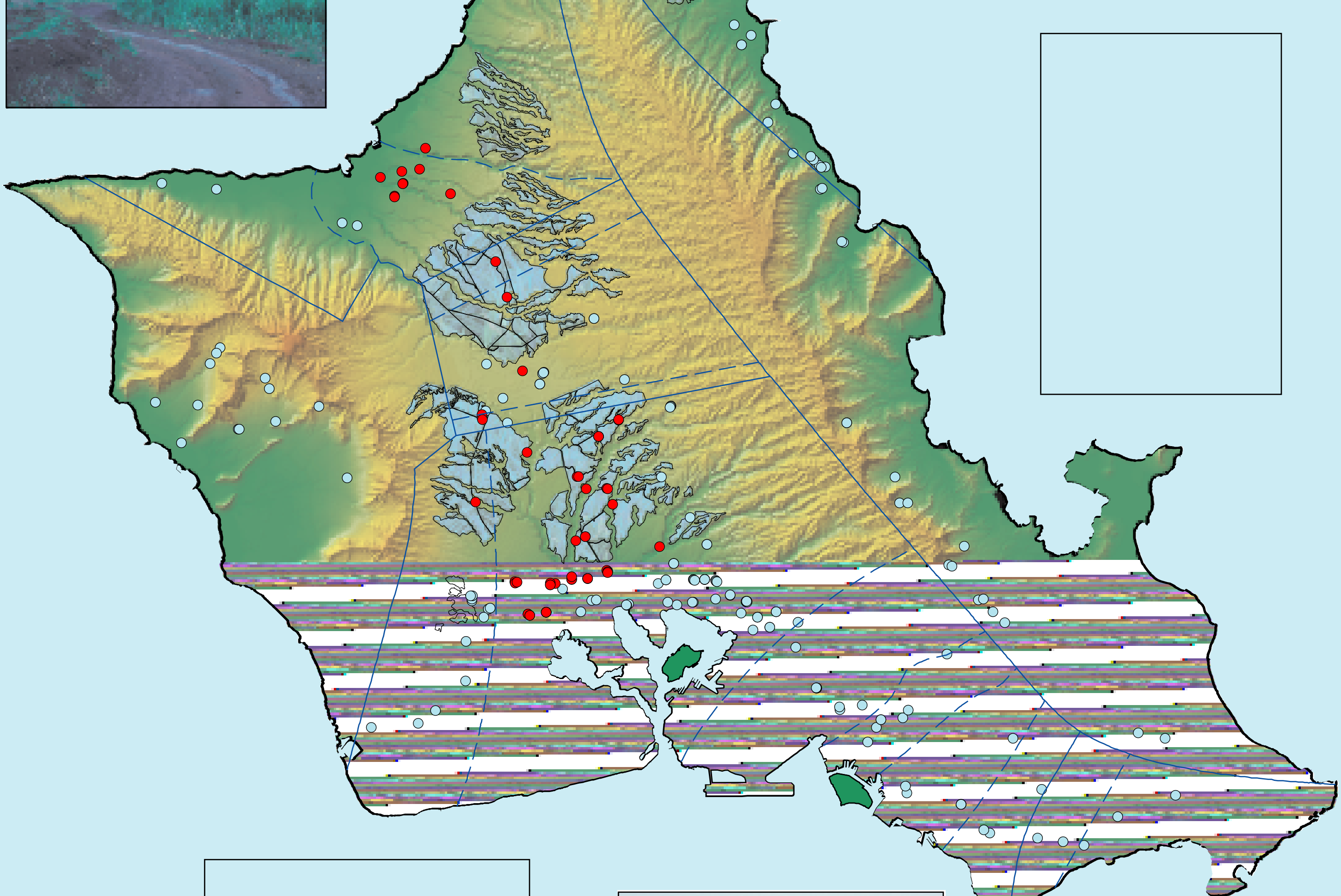
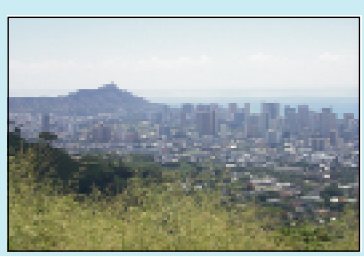
Environmental Setting and the Effects of Natural and Human-Related Factors on Water Quality and Aquatic Biota, Oahu, Hawaii

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

Water-Resources Investigations Report 03-4156





Front cover photographs clockwise starting from the northwest:

Runoff generated from a sugarcane field that was once part of the Waialua Sugar Company, which was closed in the mid-1990's.

Flow in Punaluu Stream, a perennial stream in windward Oahu.

The Koolau Range viewed from windward Oahu.

Urban Honolulu with Diamond Head in the background (view toward east Oahu).

Channelized reach of Waimalu Stream in an urbanized area of southern Oahu.

The map shows wells where water has been sampled for 1,2,3-trichloropropane in relation to areas of past and present pineapple cultivation. Wells at which 1,2,3-trichloropropane has been detected are shown in red, whereas wells at which 1,2,3-trichloropropane has not been detected are shown in blue.

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2003

U.S. DEPARTMENT OF THE INTERIOR
Gale A. Norton, Secretary

U.S. GEOLOGICAL SURVEY
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FOREWORD

The U.S. Geological Survey (USGS) is committed to providing the Nation with accurate and timely scientific information that helps enhance and protect the overall quality of life and that facilitates effective management of water, biological, energy, and mineral resources (http://www.usgs.gov/). Information on the quality of the Nation's water resources is critical to assuring the long-term availability of water that is safe for drinking and recreation and suitable for industry, irrigation, and habitat for fish and wildlife. Population growth and increasing demands for multiple water uses make water availability, now measured in terms of quantity *and* quality, even more essential to the long-term sustainability of our communities and ecosystems.

The USGS implemented the National Water-Quality Assessment (NAWQA) Program in 1991 to support national, regional, and local information needs and decisions related to water-quality management and policy (http://water.usgs.gov/nawqa). Shaped by and coordinated with ongoing efforts of other Federal, State, and local agencies, the NAWQA Program is designed to answer: What is the condition of our Nation's streams and ground water? How are the conditions changing over time? How do natural features and human activities affect the quality of streams and ground water, and where are those effects most pronounced? By combining information on water chemistry, physical characteristics, stream habitat, and aquatic life, the NAWQA Program aims to provide science-based insights for current and emerging water issues and priorities.

From 1991-2001, the NAWQA Program completed interdisciplinary assessments in 51 of the Nation's major river basins and aquifer systems, referred to as Study Units (http://water.usgs.gov/nawqa/studyu.html). Baseline conditions were established for comparison to future assessments, and long-term monitoring was initiated in many of the basins. During the next decade, 42 of the 51 Study Units will be reassessed so that 10 years of comparable monitoring data will be available to determine trends at many of the Nation's streams and aquifers. The next 10 years of study also will fill in critical gaps in characterizing water-quality conditions, enhance understanding of factors that affect water quality, and establish links between *sources* of contaminants, the *transport* of those contaminants through the hydrologic system, and the potential *effects* of contaminants on humans and aquatic ecosystems.

The USGS aims to disseminate credible, timely, and relevant science information to inform practical and effective water-resource management and strategies that protect and restore water quality. We hope this NAWQA publication will provide you with insights and information to meet your needs, and will foster increased citizen awareness and involvement in the protection and restoration of our Nation's waters.

The USGS recognizes that a national assessment by a single program cannot address all water-resource issues of interest. External coordination at all levels is critical for a fully integrated understanding of watersheds and for cost-effective management, regulation, and conservation of our Nation's water resources. The NAWQA Program, therefore, depends on advice and information from other agencies—Federal, State, interstate, Tribal, and local—as well as nongovernmental organizations, industry, academia, and other stakeholder groups. Your assistance and suggestions are greatly appreciated.

Robert M. Hirsch
Associate Director for Water

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CONVERSION FACTORS, ABBREVIATIONS, AND DATUMS

Multiply	By	To obtain
inches per year (in/yr)	2.54	centimeters per year
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
foot per mile (ft/mi)	0.1894	meter per kilometer
foot per day (ft/d)	0.3048	meter per day
million gallons per day (Mgal/d)	0.04381	cubic meter per second
pounds per acre (lb/acre)	1.14	kilogram per hectare

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

$$°C=(°F-32)/1.8$$

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

$$°F=1.8(°C) + 32$$

Water-Quality Abbreviations:
mg/L, milligrams per liter
µg/L, micrograms per liter
µg/kg, micrograms per kilogram

Other Abbreviations:
Ma, mega-annum
ppm, parts per million (equivalent to mg/kg)

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

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ABSTRACT

The island of Oahu is the third largest island of the State of Hawaii, and is formed by the eroded remnants of the Waianae and Koolau shield volcanoes. The landscape of Oahu ranges from a broad coastal plain to steep interior mountains. Rainfall is greatest in the mountainous interior parts of the island, and lowest near the southwestern coastal areas.

The structure and form of the two volcanoes in conjunction with processes that have modified the original surfaces of the volcanoes control the hydrologic setting. The rift zones of the volcanoes contain dikes that tend to impede the flow of ground water, leading to high ground-water levels in the dike-impounded ground-water system. In the windward (northeastern) part of the island, dike-impounded ground-water levels may reach the land surface in stream valleys, resulting in ground-water discharge to streams. Where dikes are not present, the volcanic rocks are highly permeable, and a lens of freshwater overlies a brackish-water transition zone separating the freshwater from saltwater. Ground water discharges to coastal springs and streams where the water table in the freshwater-lens system intersects the land surface.

The Waianae and Koolau Ranges have been deeply dissected by numerous streams. Streams originate in the mountainous interior areas and terminate at the coast. Some streams flow perennially throughout their entire course, others flow perennially over parts of their course, and the remaining streams flow during only parts of the year throughout their entire course.

Hawaiian streams have relatively few native species compared to continental streams. Widespread diverse orders of insects are absent from the native biota, and there are only five native fish, two native shrimp, and a few native snails. The native fish and crustaceans of Hawaii's freshwater systems are all amphidromous (adult lives are spent in streams, and larval periods as marine or estuarine zooplankton).

During the 20th century, land-use patterns on Oahu reflected increases in population and decreases in large-scale agricultural operations over time. The last two remaining sugarcane plantations on Oahu closed in the mid-1990's, and much of the land that once was used for sugarcane now is urbanized or used for diversified agriculture. Although two large pineapple plantations continue to operate in central Oahu, some of the land previously used for pineapple cultivation has been urbanized.

Natural and human-related factors control surface- and ground-water quality and the distribution and abundance of aquatic biota on Oahu. Natural factors that may affect water quality include geology, soils, vegetation, rainfall, ocean-water quality, and air quality. Human-related factors associated with urban and agricultural land uses also may affect water quality. Ground-water withdrawals may cause saltwater intrusion. Pesticides and fertilizers that were used in agricultural or urban areas have been detected in surface and

ground water on Oahu. In addition, other organic compounds associated with urban uses of chemicals have been detected in surface and ground water on Oahu.

The effects of urbanization and agricultural practices on instream and riparian areas in conjunction with a proliferation of nonnative fish and crustaceans have resulted in a paucity of native freshwater macrofauna on Oahu. A variety of pesticides, nutrients, and metals are associated with urban and agricultural land uses, and these constituents can affect the fish and invertebrates that live in the streams.

INTRODUCTION

In 1991, the U.S. Geological Survey (USGS) initiated the National Water-Quality Assessment (NAWQA) Program with the intent of developing long-term consistent and comparable information on streams, ground water, and aquatic ecosystems to support sound management and policy decisions. The NAWQA program is designed to assess the status and trends in the condition of our Nation's streams and ground water, and how natural and human factors affect water quality across the Nation. Study units, which are major river basins and aquifers across the Nation, represent the basic building blocks of the NAWQA Program. Since 1991, USGS scientists with the NAWQA Program have been collecting data and information in study units across the Nation to provide a framework for national and regional water-quality assessment. As part of the NAWQA program, in 1997 the USGS initiated work in the Oahu Study Unit, which is formed by the island of Oahu, Hawaii (fig. 1).

The ground-water and surface-water resources of Oahu are of significant economic, ecologic, cultural, and aesthetic importance. Ground water is used for drinking water and irrigation, and other domestic, municipal, commercial, industrial, and military purposes. Ground water also sustains coastal springs and streamflow in some areas. Streams supply irrigation water for agriculture, provide important riparian and instream habitats for many unique native species, support traditional and customary Hawaiian gathering rights and the practice of taro cultivation, and possess valued aesthetic qualities. In addition, streams affect the physical, chemical, and aesthetic quality of receiving waters, such as estuaries, bays, and nearshore waters, which are critical to the tourism-based economy of the island, recreational activities, and subsistence fishing. Because of the importance of the ground- and surface-water resources of Oahu, understanding the factors that affect water quality is essential for establishing proper management and policy decisions.

Purpose and Scope

The purpose of this report is to describe the natural and human factors that affect water quality in the Oahu Study Unit. This report describes the natural factors, including the physiography, climate, geology, soils, and hydrology, that determine the natural background water quality, and the human factors, including land use, that may affect water quality and aquatic biota.

ENVIRONMENTAL SETTING

The island of Oahu (604 mi^2) is the third largest island of the State of Hawaii and is located between longitude 158°20′W and 157º35′W and between latitude 21°15′N and 21°45′N (fig. 1). The landscape of Oahu ranges from a broad coastal plain to steep interior mountains. Topography of the island affects climate, which is characterized by mild temperatures and cool, persistent northeasterly trade winds. The structure and form of the two volcanoes in conjunction with processes that have modified the original surfaces of the volcanoes control the hydrologic setting.

Physical Setting

The island is formed by the eroded remnants of the Waianae and Koolau shield volcanoes. The Waianae Range, which is the eroded remnant of the older Waianae Volcano, forms the western part of the island and has a peak altitude of 4,025 ft at Mount Kaala, the highest peak on Oahu. The younger Koolau Range forms the eastern part of Oahu and has a peak altitude of 3,105 ft at Puu Konahuanui (fig. 1). Weathering, erosion, and slope failure have modified the original domed surfaces of the volcanoes, dissecting parts of the island into a landscape of deep valleys and steep interfluvial ridges. A gently sloping saddle, the Schofield Plateau, lies between the two mountain

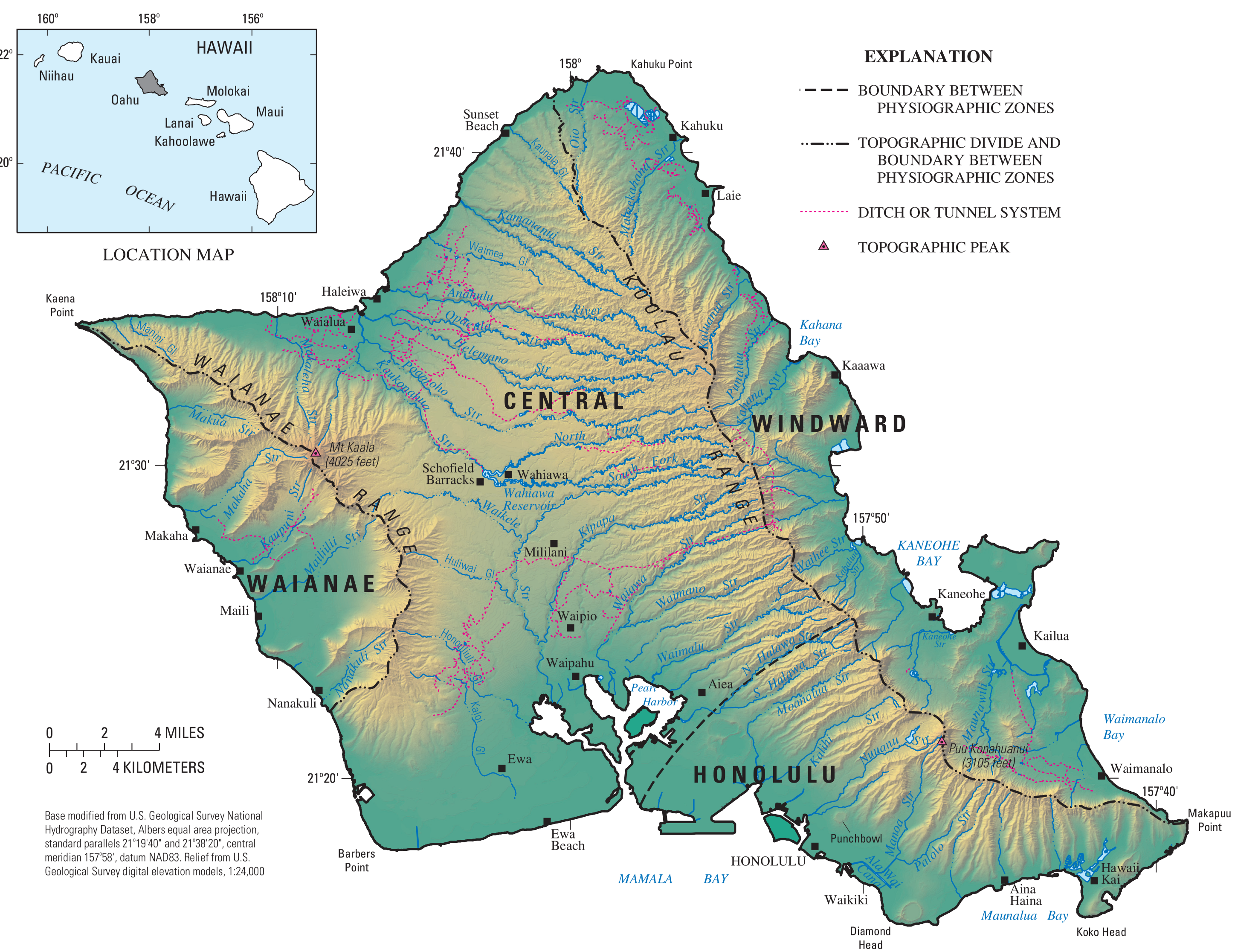


Figure 1. Selected streams, ditch systems, and other geographic features, island of Oahu, Hawaii.

ranges. A coastal plain surrounds much of the island. The capital city, Honolulu, is located in southeast Oahu.

The Oahu Study Unit can be divided into two primary physiographic zones, windward and leeward, which relate to the exposure of these areas to the northeasterly trade winds and orographic rainfall. In general, the windward area has smaller drainage basins (for drainage outlet points at the coast), higher rainfall, and perennial streams; in contrast the leeward area generally has larger drainage basins, lower rainfall, and nonperennial streamflow. The leeward area is subdivided into the Honolulu, central, and Waianae areas. The Honolulu area is highly urbanized in the coastal areas and generally undeveloped in the mountainous interior areas, and contains large U-shaped valleys. The central area is becoming increasingly urbanized, although large-scale plantation agriculture and diversified agriculture also exist, and contains the largest drainage basins on the island. The Oahu NAWQA study assessed water-quality conditions within the windward area, and the Honolulu and central areas of leeward Oahu. The Waianae area was not part of the Oahu NAWQA study.

Climate

Mild temperatures, cool and persistent northeasterly winds, a rainy season from October through April, and a dry season from May through September characterize the climate of Oahu (Blumenstock and Price, 1967; Sanderson, 1993). Topography and the location of the north Pacific anticyclone relative to the island primarily control the climate of Oahu. During the dry season the stability of the north Pacific anticyclone produces persistent northeasterly winds, known locally as trade winds, that blow 80 to 95 percent of the time. During the rainy season, migratory weather systems often move past the Hawaiian islands, resulting in less persistent trade winds that blow 50 to 80 percent of the time. Southerly winds associated with low-pressure systems can bring heavy rains to the island. The dry coastal leeward areas receive much of their rainfall because of these low-pressure systems. During heavy storms, 24-hour rainfall can exceed 10 in. over coastal areas and 20 in. over the mountainous interior of the Koolau Range (Giambelluca and others, 1984).

Temperature

The mild temperatures around the island are attributed to the large heat capacity of the surrounding ocean. At the Honolulu International Airport in the leeward area, the warmest month of the year is August, with a mean temperature of 80.5°F, and the coolest month is February, with a mean temperature of 72°F (Nullet and Sanderson, 1993). The small temperature difference between the warmest and coolest months is largely attributable to the influence of the surrounding ocean, the persistence of the cool trade winds, and the small seasonal variation in solar radiation (Blumenstock and Price, 1967; Sanderson, 1993).

In Hawaii, the average lapse rate, or decline of temperature with altitude, is about 3.6°F per 1,000 ft below an altitude of 3,900 ft, decreasing to about 3.0°F per 1,000 ft above an altitude of 3,900 ft (Nullet and Sanderson, 1993). The decrease in lapse rate above an altitude of about 3,900 ft is caused by the trade-wind inversion, in which subsiding air that warms by compression meets cooler air from below. On the basis of existing data and the estimated lapse rates, average annual temperatures on Oahu range from about 77°F near the southwest coast to less than 68°F at the higher altitudes of the Koolau Range (fig. 2) (Nullet and Sanderson, 1993).

Rainfall

Rainfall on Oahu is characterized by maxima at high altitudes and steep spatial gradients (fig. 3). Maximum mean annual rainfall is near the topographic crest of the Koolau Range and exceeds 275 in. (Giambelluca and others, 1986). Over the Waianae Range, the maximum mean annual rainfall is about 80 in. near Mount Kaala. Along the southwestern coastal areas of leeward Oahu, mean annual rainfall is less than 25 in. Mean annual rainfall changes significantly over short horizontal distances; in some places, this change can be about 80 in. over a horizontal distance of one mile. Island-wide mean annual rainfall has been estimated to be 1,977 Mgal/d (Shade and Nichols, 1996), which is equivalent to about 70 in. of annual rainfall.

The windward (northeastern) side of the island is wettest. This pattern is controlled by the orographic lifting of moisture-laden northeasterly trade winds along the windward slope of the Koolau Range, which is oriented roughly perpendicular to the direction of the trade winds. The moisture-laden air mass cools as it rises up the slopes of the Koolau Range, resulting in

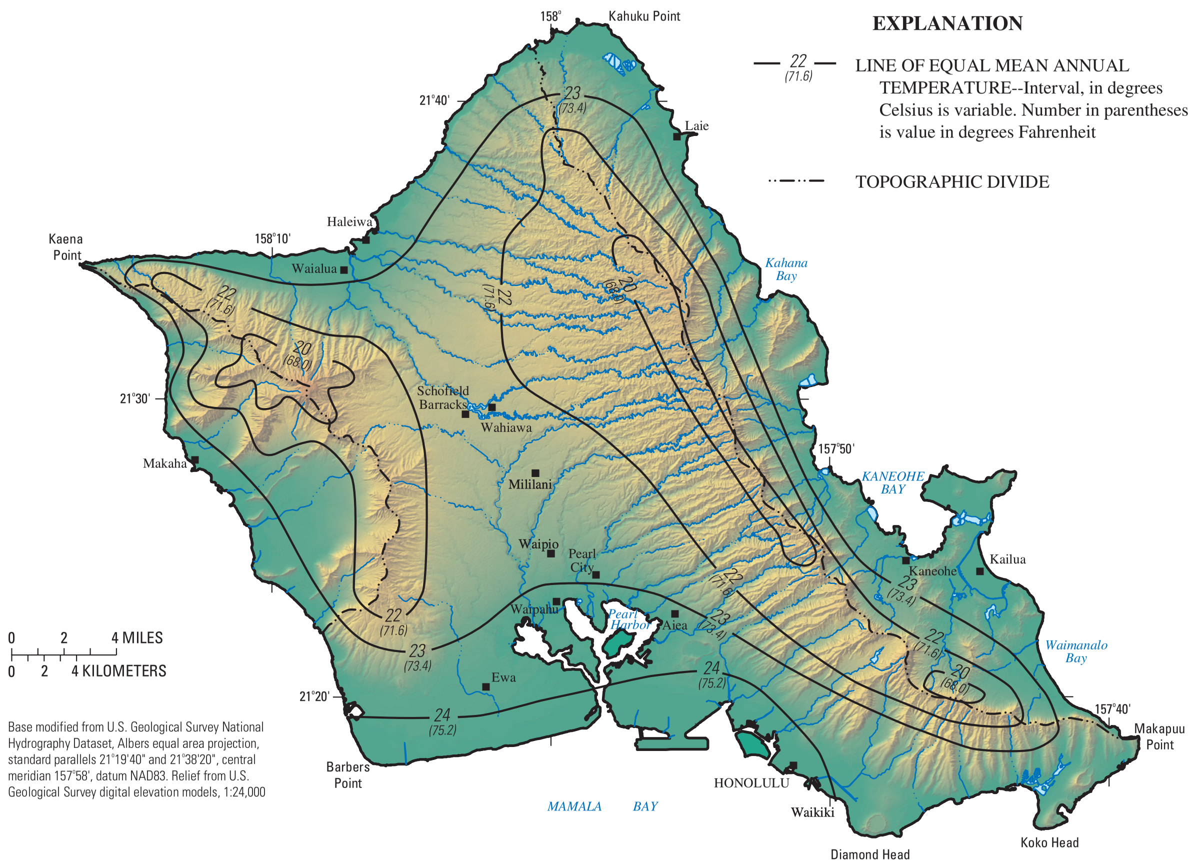


Figure 2. Mean annual air temperature, island of Oahu, Hawaii (modified from Nullet and Sanderson, 1993).

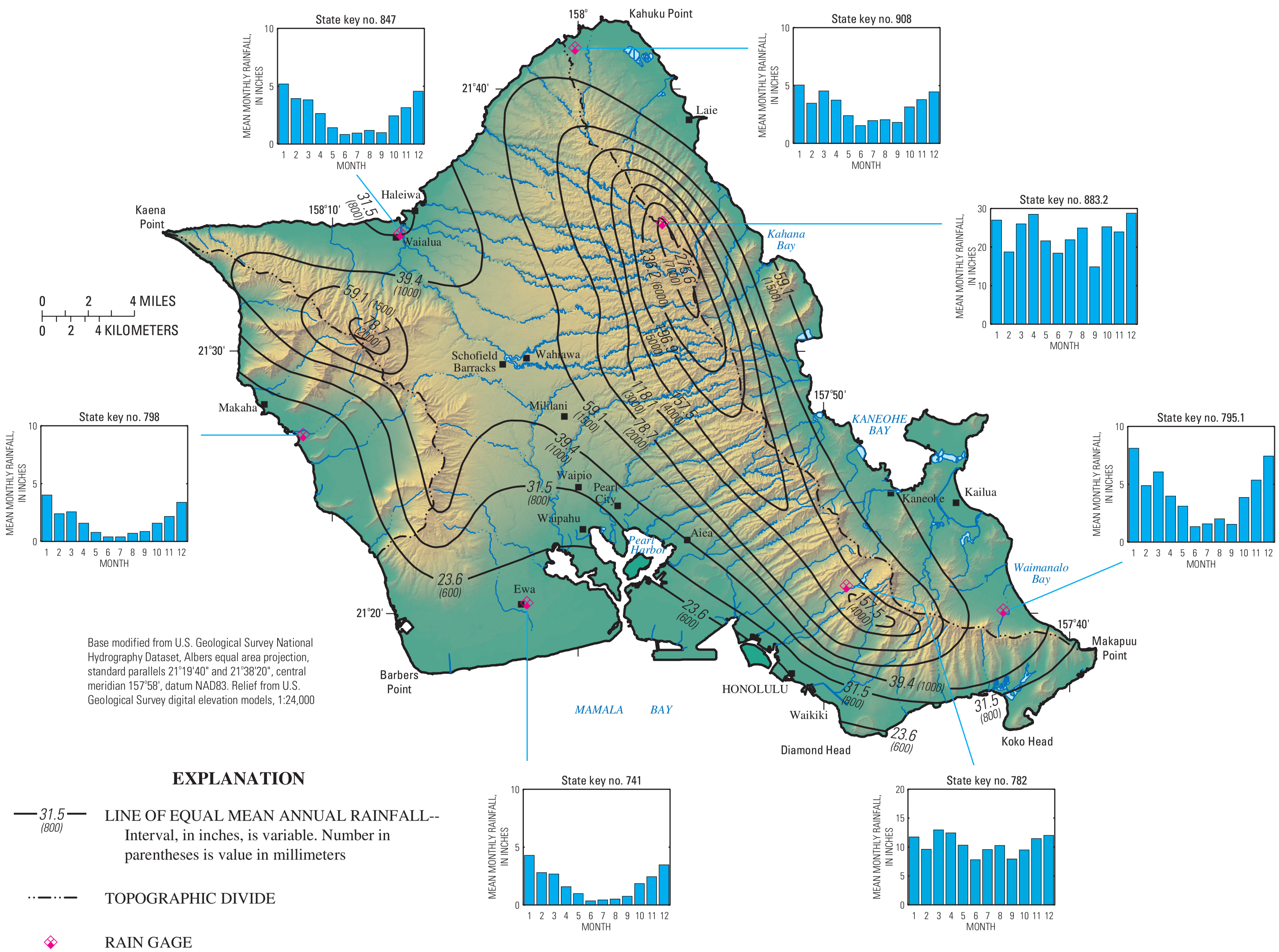


Figure 3. Mean annual rainfall, island of Oahu, Hawaii, and mean monthly rainfall at selected rain gages (modified from Giambelluca and others, 1986).

condensation, cloud formation, and high rainfall near the crest of the Koolau Range. Following its descent down the leeward slopes of the Koolau Range, the partially desiccated air is orographically lifted up the slopes of the Waianae Range, which results in a smaller rainfall maximum near Mount Kaala. Because the air loses moisture during its ascent over a mountain barrier, the driest areas on Oahu are near the coast on the leeward (southwestern) sides of the Koolau and Waianae Ranges. This is commonly known as the rain-shadow effect.

Solar Radiation

Solar radiation (insolation) consists of both direct-beam radiation, which reaches the surface from the direction of the sun, and diffuse radiation, which has been scattered or reflected and reaches the surface from directions other than directly from the sun. The atmosphere scatters, absorbs, refracts, and reflects solar radiation, which reduces the intensity of solar radiation at the surface. On clear days, insolation increases with altitude because the air mass penetrated by the solar radiation decreases with altitude.

The distribution of solar radiation (insolation) near the land surface on Oahu (fig. 4) is largely controlled by the cloud pattern over the island. Because of the orographic effect, clouds are most prevalent at higher altitudes, and this is where insolation is lowest. Insolation is greatest near the southern and western coasts where clouds are less prevalent.

Pan Evaporation

Pan evaporation is the main measurement used in Hawaii to assess the amount of water loss by evapotranspiration, which is the loss of water to the atmosphere by the combination of transpiration of plants and direct evaporation from plant, land, and water surfaces. Evapotranspiration is a major component of the hydrologic budget on Oahu. In the Honolulu area, for example, evapotranspiration was estimated to be about 40 percent of the total water (rainfall plus irrigation) falling on or applied to the ground surface during 1946–75 (Giambelluca, 1983). For 1980’s land-use conditions on the island of Oahu, Shade and Nichols (1996) estimated that about 914 Mgal/d, or 46 percent of the island-wide annual rainfall, is lost to the atmosphere as evapotranspiration.

Over the island of Oahu, pan evaporation minima exist at the higher altitudes of the Koolau and Waianae Ranges (fig. 5). Near the crest of the Koolau Range, mean annual pan evaporation may be as low as 20 in. Pan evaporation rates are highest along the southern coast of the island, and may exceed 90 in/yr. For comparison, the computed evaporation rate over the open ocean is 65 in/yr (Seckel, 1962). As with rainfall, the spatial distribution of pan evaporation on Oahu is related to topography. At high altitudes (where sunlight intensity is reduced because of clouds, humidity is high, and temperatures are low) pan-evaporation rates are reduced to 30 percent of the open-ocean rate. Pan evaporation rates along the southern coast of Oahu exceed the open ocean rate due to positive heat advection (Ekern and Chang, 1985). Evaporation rates are highest during the drier summer months, when maximum sunlight and trade-wind flow also are highest (Ekern and Chang, 1985).

Geologic Setting

The evolution of Hawaiian volcanoes generally progresses through four stages: preshield, shield, postshield, and rejuvenated. However, not all Hawaiian volcanoes have a postshield stage or a rejuvenated stage. The preshield stage is the earliest, submarine phase of activity. Lava from the preshield stage consists predominantly of alkalic basalt (basalt that is low in silica and high in the alkalies sodium and potassium). Lava from the principal stage of volcano building, called the shield stage, consists of fluid tholeiitic basalt (silica-saturated basalt that is poor in sodium and potassium) that characteristically forms thin flows. This basalt forms during submarine as well as subaerial eruptions and is composed primarily of calcic plagioclase feldspar and pyroxene. A large central caldera can form during the preshield or shield stages and might later be partly or completely filled during subsequent eruptions. Thousands of lava flows originate from the central caldera and from two or three rift zones that radiate out from the central part of the volcano. The shield stage is the most voluminous phase of eruptive activity, during which more than 95 percent of the volcano is formed. The postshield stage is marked by a change in lava chemistry and character, and longer periods between eruptions. Postshield-stage lava includes alkalic basalt and more viscous ankaramite, hawaiite, mugearite, and trachyte. After a period of quiescence, lava might issue from isolated vents on the volcano during the rejuvenated stage.

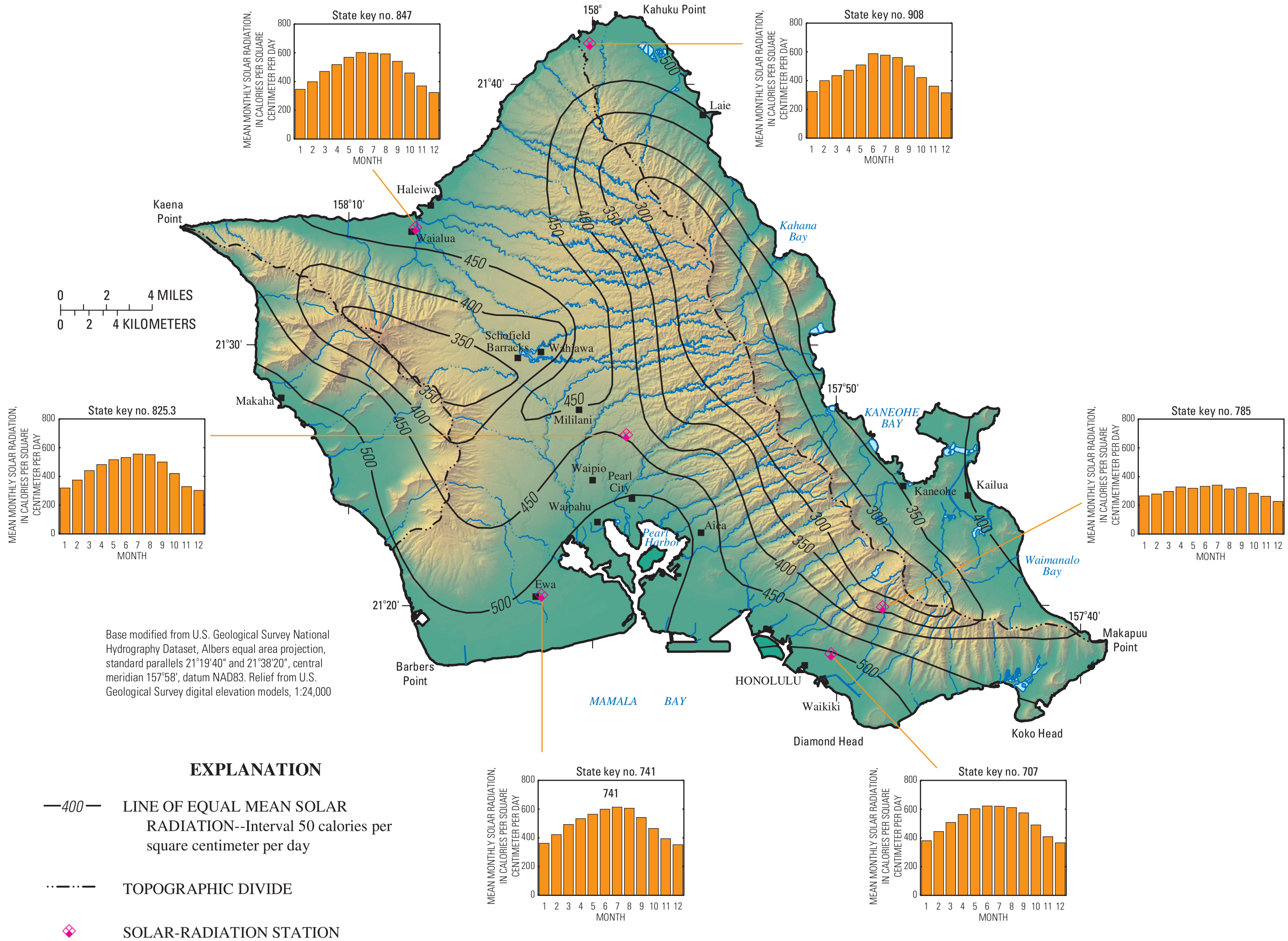


Figure 4. Mean annual solar radiation (State of Hawaii, 2002a), island of Oahu, Hawaii, and mean monthly solar radiation at selected stations (How, 1978).

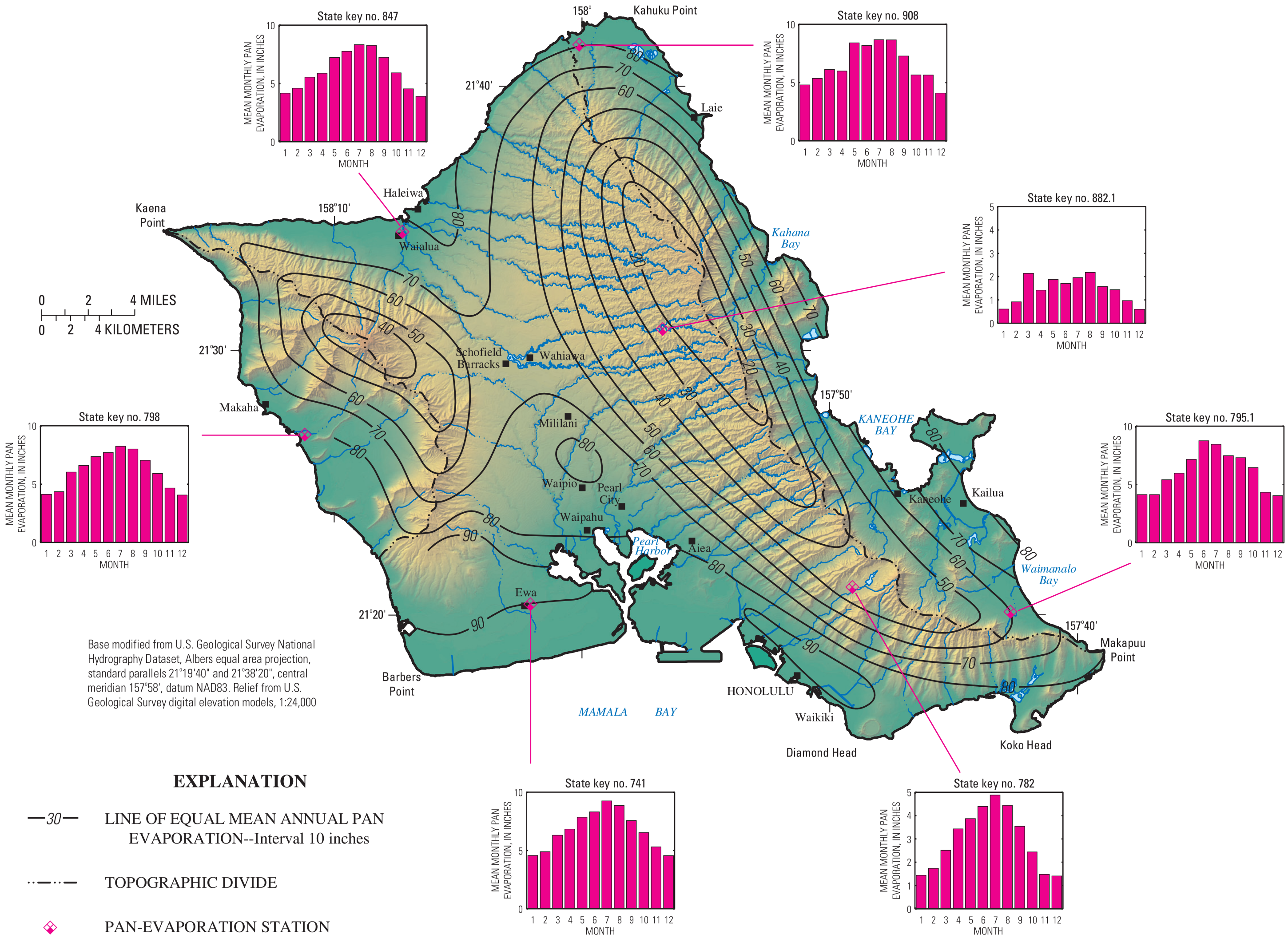


Figure 5. Mean annual pan evaporation, island of Oahu, Hawaii, and mean monthly pan evaporation at selected stations (modified from Ekern and Chang, 1985).

Volcanic rocks in Hawaii can be divided into three main groups on the basis of modes of emplacement: lava flows, dikes, and pyroclastic deposits. In general, lava flows that erupt from rift zones are less than 10 ft thick and are either pahoehoe, which is characterized by smooth or ropy surfaces, or aa, which contains a massive central core sandwiched between rubbly clinker layers. Aa flows are typically more abundant at greater distances from eruptive centers (Lockwood and Lipman, 1987).

Dikes are thin, near-vertical sheets of massive rock that intrude existing rocks, such as lava flows. Dikes commonly are exposed by erosion within the rift zones of volcanoes, including the Waianae and Koolau Volcanoes (see for example Takasaki and Mink, 1985; Walker, 1987). In the central part of a rift zone, known as the dike complex, dikes may number as many as 1,000 per mile of horizontal distance and compose 10 percent or more of the total rock volume (Takasaki and Mink, 1985). The number of dikes decreases toward the outer edges of a rift zone. At the outer part of the rift zone, within the marginal dike zone, dikes usually constitute less than 5 percent of the total rock volume (Takasaki and Mink, 1985). Wentworth and Macdonald (1953) estimated that 200 dikes are needed to supply enough lava to vertically build 1,000 ft of a shield volcano.

Pyroclastic rocks form by explosive volcanic activity and are deposited by transport processes related to this activity. Pyroclastic rocks, such as ash, cinder, and spatter, can be deposited during all of the subaerial stages of eruption and probably form less than 1 percent of the mass of a Hawaiian volcano (Wentworth and Macdonald, 1953).

The geology of Oahu has been described by numerous investigators (see for example Stearns and Vaksvik, 1935; Palmer, 1927; Palmer, 1946; Winchell, 1947; Wentworth and Winchell, 1947; Wentworth, 1951; Macdonald and others, 1983; Stearns, 1985). Stearns (1939) published a detailed geologic map of Oahu. Langenheim and Clague (1987) described the stratigraphic framework of volcanic rocks for the entire island of Oahu. Presley and others (1997) suggested a revised stratigraphic nomenclature for Waianae Volcano.

The island of Oahu is formed primarily by the shield-stage lavas of the older Waianae Volcano to the west and the younger Koolau 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 (fig. 6). The primary rift zones of the Waianae Volcano trend roughly northwest and south, and the third, lesser rift zone trends northeast. The primary rift zones of the Koolau Volcano trend northwest and southeast, and the third, subordinate rift zone trends southwest. The rift zones are marked by numerous vertical to nearly vertical intrusive dikes (Takasaki and Mink, 1985; Walker, 1987).

Waianae Volcano

Exposed rocks of the Waianae Volcano are made up of the Waianae Volcanics, which includes (1) the shield-stage lavas (Lualualei Member) of tholeiitic basalt, (2) the transitional or late shield-stage lavas (Kamaileunu Member) of mainly tholeiitic basalt, alkalic basalt, hawaiite, and rare ankaramite, (3) the postshield-stage lavas (Palehua Member) of hawaiite with minor alkalic basalt and mugearite, and (4) the younger postshield-stage lavas (Kolekole Member) of alkalic basalt (Sinton, 1986; Presley and others, 1997). The lava flows from the shield-stage Lualualei Member are mainly thin-bedded pahoehoe, ranging in thickness from about 5 to 75 ft and averaging about 25 ft. Lava flows of the Lualualei Member typically have dips of 4 to 14 degrees. Flows of the Kamaileunu Member are mainly pahoehoe and range in thickness from 10 to 120 ft, averaging about 40 ft. Flows of the Palehua Member are mainly aa and commonly have thicknesses ranging from 50 to 100 ft (Stearns and Vaksvik, 1935; Macdonald, 1940).

Potassium-argon dating of the Waianae Volcanics indicates an age of about 2.9 to 3.9 Ma (mega-annum [million years]) corresponding to the Pliocene epoch (Doell and Dalrymple, 1973; Presley, 1994; Presley and others, 1997). Exposed rocks of the Lualualei Member have ages of about 3.54 to 3.93 Ma, and exposed rocks of the Kamaileunu Member have ages of about 3.5 to 3.08 Ma (Guillou and others, 2000). Rocks of the Kolekole Member have an age of about 2.90 to 2.97 Ma (Presley and others, 1997).

Koolau Volcano

Exposed rocks of the younger Koolau Volcano are subdivided into the Koolau Basalt and the Honolulu Volcanics. The Koolau Basalt consists primarily of shield-stage tholeiitic basalt, and the rejuvenated-stage

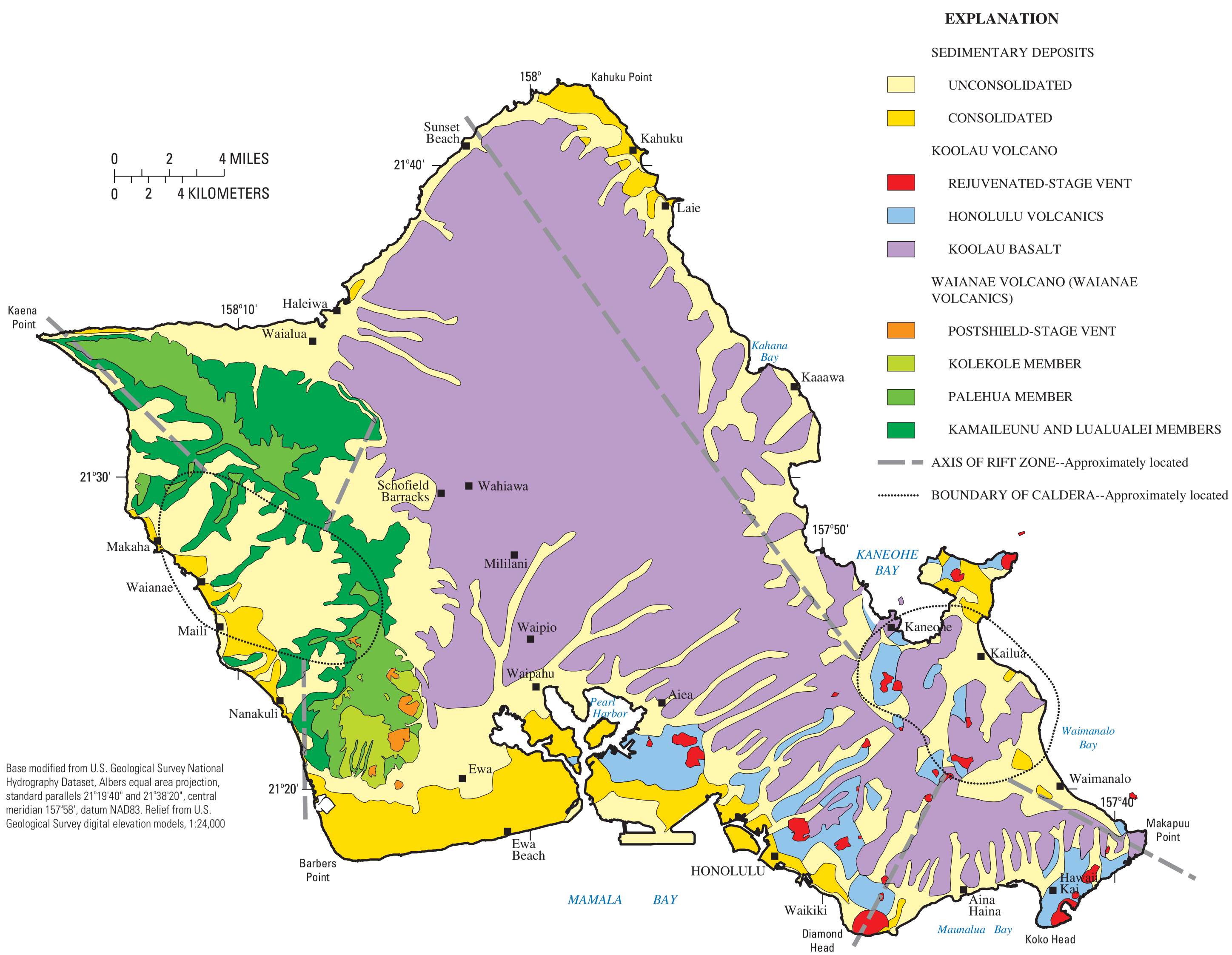


Figure 6. Generalized surficial geology, island of Oahu, Hawaii (modified from Stearns, 1939; Langenheim and Clague, 1987; and Presley and others, 1997).

Honolulu Volcanics consists of alkalic basalt, basanite, and nephelinite to melilitite (Langenheim and Clague, 1987).

Potassium-argon determinations of Koolau Basalt indicate an age of 1.8 to 2.6 Ma (Doell and Dalrymple, 1973) corresponding to the Pliocene epoch. The lava flows from the shield-stage Koolau Basalt are typically thin-bedded, with an average flow thickness of about 10 ft, and have dips of 3 to 10 degrees (Stearns and Vaksvik, 1935). Few soil or tuff layers interrupt the sequence of shield-stage lavas. Wentworth (1951) estimated that throughout the whole mass of the volcano, tuff lenses make up less than 1 or 2 thousandths of the whole section.

During the shield stage, lava flowing westward from the Koolau Volcano was deflected northward and southward by the preexisting Waianae Volcano. The central saddle area between the two volcanoes was formed by Koolau Basalt banking up against and being deflected by the Waianae Volcano. Within the central saddle, dips of the Koolau Basalt are invariably less than 5 and rarely more than 3 degrees (Stearns and Vaksvik, 1935, p. 34).

The Honolulu Volcanics erupted from more than 50 vents, which are confined to the southeastern part of Oahu, and deposited on an already much-eroded, mature topography of the Koolau shield (Wentworth, 1951). The Honolulu Volcanics is of limited areal extent and is most notably marked by tuff cones such as Diamond Head, Punchbowl, and Koko Head. However, the Honolulu Volcanics also consists of cinder cones, ash deposits, spatter cones, and lava flows. Potassium-argon dating of various Honolulu Volcanics indicates ages from 0.031 Ma (Gramlich and others, 1971) to 1.13 Ma (Lanphere and Dalrymple, 1980) corresponding to the Pleistocene epoch. Age dates for the same flow, however, may have varied by an order of magnitude (Macdonald and others, 1983).

Geochemistry of the Volcanic Rocks

Common minerals of the shield-building tholeiitic rocks on Oahu include pyroxene, olivine, plagioclase feldspar (anorthite and albite), magnetite, and ilmenite (table 1). Apatite is found in small amounts but is widely distributed in the Koolau Basalt (Wentworth and Winchell, 1947). The tholeiitic volcanic rocks on Oahu contain minerals that have high concentrations of aluminum, iron, silica, calcium, and magnesium (table 2).

The volcanic rocks also contain numerous trace elements, including chromium, zinc, nickel, lead, and others (table 3). Chromium concentrations commonly range between about 100 and 900 ppm (parts per million), zinc concentrations range from about 100 to 200 ppm, and nickel concentrations range from about 100 to 700 ppm (table 3). Analyses of volcanic rocks from Oahu by McMurtry and others (1995) indicated concentrations of mercury from 0.017 to 0.044 ppm.

Geologic Modification Processes

The volcanoes that formed the island of Oahu have undergone significant modification by processes such as subsidence, weathering, erosion, and deposition. Subsidence has drowned coastal areas and subaerially formed valleys. Chemical weathering has led to decomposition of volcanic rocks and leaching of soluble decomposition products. Large-scale mass wasting, which is the downslope movement of earth materials under the influence of gravity, has removed much of the western part of Waianae Volcano and the northeastern part of Koolau Volcano. Streams have further modified the volcanoes by incising deep valleys and transporting material to coastal areas. Deposits of marine and terrestrial sediments have formed a coastal plain of varying width around the island.

Subsidence

Subsidence of Oahu was contemporaneous with shield development. Moore (1987) estimated that most Hawaiian volcanoes have subsided 6,500 to 13,000 ft since reaching the ocean surface. Andrews and Bainbridge (1972) suggested that submarine valleys off the northeastern coast of Oahu were originally subaerial features that have drowned as the island subsided. Some of these submarine valleys can be traced to depths of at least 6,600 ft below sea level (Shepard and Dill, 1966), which may indicate that Oahu has subsided at least 6,600 ft. Hunt (1996) indicated that subsidence of Oahu was mainly prior to rejuvenated Koolau volcanism because Honolulu Volcanics lies on or is intercalated with only the uppermost of the sedimentary units on the coastal plain.

Weathering and Erosion

The processes of weathering and erosion contribute to the down-cutting of the original volcanic domes that formed the island of Oahu. Although erosion can

Table 1. Selected minerals in Hawaiian rocks

Mineral	Composition	Comments
Anatase	TiO_2	titanium oxide
Apatite	$Ca_5(PO_4)_3(F,Cl,OH)$	phosphate
Biotite	$K(Mg,Fe)_3AlSi_3O_{10}(OH,F)_2$	silicate (mica)
Calcite	$CaCO_3$	carbonate
Chlorite	$(Mg,Fe,Al)_6(Si,Al)_4O_{10}(OH)_8$	silicate
Cristobalite	SiO_2	silicate
Feldspar		
Orthoclase	$KAlSi_3O_8$	silicate (potassium feldspar)
Anorthoclase	$(K,Na)AlSi_3O_8$	silicate (feldspar between orthoclase and albite)
Plagioclase (albite)	$NaAlSi_3O_8$	silicate (sodium end member of plagioclase)
Plagioclase (anorthite)	$CaAl_2Si_2O_8$	silicate (calcium end member of plagioclase)
Gibbsite	$Al(OH)_3$	aluminum hydroxide
Goethite	$FeO(OH)$	iron oxide hydroxide
Halloysite	$Al_2Si_2O_5(OH)_4$ and $Al_2Si_2O_5(OH)_4 \cdot 2H_2O$	clay mineral
Hematite	Fe_2O_3	iron oxide
Ilmenite	$FeTiO_3$	iron titanium oxide
Kaolinite	$Al_2Si_2O_5(OH)_4$	silicate (1:1 clay mineral)
Limonite	$FeO(OH) \cdot nH_2O$	hydrated iron oxide hydroxide
Magnetite	Fe_3O_4	iron oxide
Melilite	$(Ca,Na)_2(Al,Mg,Fe)(Si,Al)_2O_7$	silicate (feldspathoid)
Montmorillonite	$(Na,Ca)(Al,Mg)_6(Si_4O_{10})_3(OH)_6 \cdot nH_2O$	silicate (2:1 clay mineral)
Nepheline	$(Na,K)AlSiO_4$	silicate (feldspathoid)
Olivine	$(Mg,Fe)_2SiO_4$	silicate
Pyroxene		
Hypersthene	$(Mg,Fe)SiO_3$	silicate
Pigeonite	$(Mg,Fe,Ca)_2Si_2O_6$	silicate
Augite	$(Ca,Na)(Mg,Fe,Al,Ti)(Si,Al)_2O_6$	silicate
Quartz	SiO_2	silicate
Rutile	TiO_2	titanium oxide

Table 2. Major-element geochemistry of volcanic rocks on Oahu, Hawaii

[min., minimum; max., maximum; avg., average; n, number of samples; all values expressed as weight, in percent; --, no value reported]

	Waianae Volcanics (tholeiitic basalt)[1]				Koolau Basalt[2]				Honolulu Volcanics[3]			
Constituent	min.	max.	avg.	n	min.	max.	avg.	n	min.	max.	avg.	n
SiO_2	48.83	51.48	50.58	13	48.88	53.78	51.91	71	35.76	46.18	40.24	41
TiO_2	2.07	3.97	2.78	13	1.41	2.53	2.08	71	1.87	3.22	2.42	41
Al_2O_3	12.67	16.98	13.91	13	11.34	15.83	14.02	71	9.65	15.77	12.06	41
Fe_2O_3	11.19	14.34	12.49	13	10.65	12.61	11.43	71	12.44	20.15	14.89	41
MnO	0.12	0.17	0.15	13	0.14	0.22	0.16	71	0.19	0.28	0.23	41
MgO	3.56	9.75	6.43	13	5.46	15.17	7.62	71	5.60	17.35	12.43	41
CaO	8.22	10.56	9.48	13	7.55	10.24	9.28	71	8.40	15.63	11.80	41
Na_2O	1.92	3.23	2.48	13	1.77	3.16	2.74	70	0.89	5.41	3.63	41
K_2O	0.28	0.99	0.53	13	0.09	0.82	0.39	71	0.21	1.81	0.96	41
P_2O_5	0.19	0.67	0.38	13	0.18	0.36	0.28	71	0.34	1.53	0.93	41
Cl	--	--	--	--	--	--	--	--	0.01	0.21	0.08	26
F	--	--	--	--	--	--	--	--	0.04	0.18	0.08	26
S	--	--	--	--	--	--	--	--	0.01	0.13	0.03	21
Cr_2O_3	--	--	--	--	--	--	--	--	0.01	0.10	0.07	34
NiO	--	--	--	--	--	--	--	--	0.01	0.06	0.04	13

[1]Samples analyzed by X-ray fluorescence (Guillou and others, 2000)

[2]Samples analyzed by X-ray fluorescence; picrite basalt sample 17a not included (Frey and others, 1994)

[3]Samples analyzed by wet chemistry (Clague and Frey, 1982); results normalized to reflect loss of water and carbon dioxide

Table 3. Trace-element geochemistry of volcanic rocks on Oahu, Hawaii

[min., minimum; max., maximum; avg., average; n, number of samples; all values expressed in parts per million (ppm); --, no value reported]

Constituent	Waianae Volcanics (tholeiitic basalt)[1]				Koolau Basalt[2]				Honolulu Volcanics[3]			
	min.	max.	avg.	n	min.	max.	avg.	n	min.	max.	avg.	n
Rb	--	--	--	--	0.1	11.9	4.9	70	7	51	24	15
Cs	--	--	--	--	0.024	0.124	0.059	14	0.4	0.8	0.7	11
Sr	--	--	--	--	273	487	415	70	520	2,150	1,119	32
Ba	--	--	--	--	49	149	95	71	325	1,065	727	30
Sc	--	--	--	--	20.4	27.8	25.0	49	14	29	24	30
Y	--	--	--	--	15.1	52.3	23.7	70	18	32	25	8
La	--	--	--	--	6.44	19.2	12.13	49	18	109	62	30
Zr	--	--	--	--	95	183	150	71	110	240	163	30
Hf	--	--	--	--	2.17	4.11	3.49	49	2.5	5.3	3.4	30
V	--	--	--	--	186	293	237	71	190	1,300	301	31
Nb	--	--	--	--	5.4	12.3	9.3	71	24	55	41	8
Ta	--	--	--	--	0.3	0.76	0.55	49	1.2	4.6	2.6	29
Cr	198	742	464	25	67	890	322	71	38	600	459	30
Co	--	--	--	--	36.6	66.9	42.7	49	42	75	66	30
Ni	134	644	280	25	79	670	176	71	80	460	290	31
Cu	70	215	123	25	--	--	--	--	30	125	63	31
Zn	89	255	163	25	93	158	110	71	100	175	126	30
Cd	18	65	43	6	--	--	--	--	--	--	--	--
Ga	--	--	--	--	15.5	22.4	20.4	70	15.0	21.0	18.2	8
Pb	--	--	--	--	--	--	--	--	3.3	8.3	5.2	8
Ce	--	--	--	--	17	42	30	71	41	176	111	30
Th	--	--	--	--	0.16	0.7	0.48	45	2.0	10.9	6.2	30
Nd	--	--	--	--	12	33.8	21.0	49	20	73	50	30
Sm	--	--	--	--	3.17	8.92	5.41	49	5.0	17.0	11.5	30
Eu	--	--	--	--	1.12	3.01	1.85	49	1.84	4.88	3.41	30
Tb	--	--	--	--	0.42	1.53	0.80	49	0.7	1.9	1.3	30
Yb	--	--	--	--	1.21	3.18	1.77	49	1.2	2.6	1.7	30
Lu	--	--	--	--	0.18	0.5	0.26	49	0.14	0.42	0.27	30

[1]Herlicska, 1967

[2]Frey and others, 1994

[3]Clague and Frey, 1982

occur in the absence of weathering, weathering processes that break or soften rocks commonly enhance erosion.

Weathering involves physical and chemical processes that respectively lead to the physical disintegration and the decomposition of rocks. Although physical weathering occurs on Oahu, chemical weathering is the dominant weathering process on the island. Decomposition of rocks by chemical weathering is enhanced by high rainfall, abundant vegetation, and generally warm temperatures on Oahu. The processes of hydrolysis, hydration, solution, carbonation, oxidation, and cation exchange generally are active in decomposition of Hawaiian rocks (Macdonald and others, 1983). Because the processes of hydrolysis, hydration, and solution are dependent on the presence of water, they are more active in wetter areas than in drier areas. One of the important acids involved in chemical weathering is carbonic acid (Li, 1988). Carbonic acid is commonly formed when water combines with carbon dioxide released in the soil by biological activity and, to a lesser degree, with carbon dioxide derived from the atmosphere. Decomposition of rocks by carbonic acid commonly produces carbonates and bicarbonates and, thus, this weathering process is commonly referred to as carbonation. Acids present in rainfall and humic acids derived from decaying vegetation also can enhance decomposition of rocks.

Minerals that crystallize at high temperatures during the early cooling stages of the volcanic rocks tend to be least stable and weather most rapidly in the surface environment, whereas minerals that form at lower temperatures are more stable. Olivine crystallizes early and is most readily weathered. After olivine, the minerals that are common in volcanic rocks on Oahu and most readily weathered are, in order of ease of alteration, magnetite, anorthite, pyroxene, and albite (Macdonald and others, 1983).

During the process of chemical weathering of volcanic rocks, soluble decomposition products including silica, calcium, potassium, magnesium, and sodium are carried away with downward percolating water. Clay minerals (including kaolinite, halloysite, and montmorillonite) and oxides and hydroxides (including hematite, magnetite, gibbsite and goethite) are less soluble decomposition products and are commonly less mobile (Macdonald and others, 1983; Miller, 1987). The oxide and hydroxide minerals are abundant in highly weathered soils on Oahu.

The effects of chemical weathering can extend to significant depths below the surface. The effects of chemical weathering proceed in a downward direction, resulting in a typical geologic profile consisting of several feet of soil and subsoil underlain by a few tens or hundreds of feet of saprolite, which is underlain by fresher volcanic rock. Saprolite is weathered rock retaining the structural and textural features of the parent rock. Hunt (1996) indicated that weathering intensity and saprolite thickness increase with rainfall and estimated that saprolite is typically less than 100 ft thick in areas where rainfall is less than 50 in/yr and about 100 to 300 ft thick where rainfall is between 50 to 80 in/yr. Beneath stream channels, where percolating water is almost always present, depth of weathering may be considerably greater.

Erosion involves a group of processes that lead to the removal of earth materials from the surface. Destruction and modification of the land surface can be brought about by forces related to gravity, surface-water runoff, ocean waves, and wind. Mass wasting includes rockfalls, landslides, mudflows, soil avalanches, and soil creep. Mass wasting, in combination with transportation of earth materials by running water, waves, and wind, accounts for most of the erosion on Oahu.

Using information from a side-looking sonar system, Moore and others (1989) identified major submarine mass-wasting deposits, including the Waianae slump and Nuuanu debris avalanche off the west and northeast coasts of Oahu, respectively. These landslides modified the shapes of the volcanoes that form the island and enhanced erosion processes on the steepened slopes. The slope failures moved in directions approximately perpendicular to the major rift zones of the Waianae and Koolau Volcanoes (Moore and others, 1989).

Whereas waves can erode the land during all subaerial stages of volcanic activity, during the shield stage of volcanic activity, when the interval between successive lava flows is short, erosion of the land surface by streams is likely ineffective because the rocks are largely unaffected by weathering and are highly permeable, and little rain runs off to the ocean. However, following the shield stage of volcanic activity, during the period of volcanic quiescence, weathering of the land surface and erosion by streams can be significant. The rate of erosion by streams on Oahu has been estimated to range from about 1 to 6 in. per thousand years (Li, 1988).

Erosion by streams has resulted in formation of valleys that have been incised more than a thousand feet in the Koolau and Waianae Ranges. In windward Oahu and the western part of the Waianae Range, mass wasting and erosion have resulted in coalescence of valleys and formation of large U-shaped, amphitheater-headed valleys. In the Honolulu area, large valleys have not coalesced, and are narrower than those in windward Oahu. In some areas, rejuvenated-stage volcanics and alluviation have flattened the valley floors. Stearns and Vaksvik (1935) indicated that an amphitheater-headed valley also existed in the eastern part of the Waianae Range. In general, the remaining valleys on the island are in a more youthful stage of dissection, and are narrower and V-shaped. In central Oahu, where slopes are gentle, V-shaped gulches have formed in Koolau Basalt and are separated by broad interfluves.

On Oahu, parts of the Waianae Volcano had been eroded prior to being covered by Koolau Basalt. Thus, the Waianae Volcanics is separated from Koolau Basalt by an erosional unconformity. Stearns and Vaksvik (1935) suggested that the Waianae Range had a well-developed stream pattern prior to the formation of the central saddle between the volcanoes because Koolau Basalt occupies a former amphitheater-headed valley.

Deposition

Following the period of extensive erosion during which valleys were deeply incised, the valleys were filled in by marine and terrestrial sediments during a period when relative sea level was higher than it is today. Toward the lower reaches of the valleys below an altitude of about 30 ft, valley-fill deposits consist of terrestrial sediments that interfinger with marine sediments and limestone units. The geologic sequence reflects changes in relative sea level associated with island subsidence and glacioeustatic sea-level fluctuations during the Pleistocene (Stearns and Chamberlain, 1967). Inland, above an altitude of about 30 ft, the base of the valley-fill material typically consists of highly weathered and compact old alluvium, which is mantled with more recent, unconsolidated alluvium and colluvium. Old alluvium consists of terrestrial sediments, varying in size from fine-grain particles to boulders, which have been weathered and compacted into a soft, coherent mass (Wentworth, 1951). The old alluvium may be hundreds of feet thick at lower altitudes, but at altitudes above about 400 to 600 ft, old alluvium may be nonexistent. Honolulu Volcanics is interbedded with alluvium and colluvium in some valleys, most notably those in Honolulu.

Wells drilled in and near valley mouths provide evidence for a lower stream base level than exists today. For example, Palmer (1927, 1946) used information from wells to define structural contours for the top of the Koolau Basalt beneath the coastal sedimentary deposits in the Honolulu area (fig. 7), and identified reentrant forms that represent the original, subaerially formed valley incisions. The reentrant near the mouth of Nuuanu Stream valley suggests that this valley was incised when base level was at least 800 ft lower than it is today. The valley likely was incised to a depth greater than 800 ft; however, well coverage across the valley mouth is insufficient to define the original valley cross section and maximum depth of incision. Within the original channels of Manoa, Nuuanu, and Kalihi Stream valleys of Honolulu, the thickness of the valley-fill deposits likely exceeds 1,000 ft. Stearns and Vaksvik (1935) described a well in west Oahu that penetrated 1,200 ft of valley fill.

Deposits of terrestrial and marine sediments and reef limestone form a coastal plain of varying width along the shore of Oahu. The coastal plain extends more than 5 mi inland near Pearl Harbor and is less than 1,000 ft wide along parts of the north shore of the island. 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. In northern Oahu, the coastal deposits are as much as 500-ft thick near the coast (Dale, 1978).

Hydraulic Conductivity of the Rocks

Hydraulic conductivity is a quantitative measure of the capacity of a rock to transmit water. The hydraulic conductivity of a rock can be qualitatively described by permeability. Permeability describes the ease with which fluid can move through rock. The permeability of volcanic rocks is variable and depends on many factors including the mode of emplacement and amount of weathering. Lava chemistry and topography also can affect permeability.

The primary aquifers on Oahu are highly permeable and are formed by layered sequences of thousands of dike-free lava flows outside of the rift zones. Within the rift zones, intrusive dikes reduce the overall permeability of the rocks and impede the flow of water to the coast. Weathering reduces the permeability of all types of volcanic rocks. The thickness of a lava flow can depend on the lava chemistry and the topography over which it cooled. Thicker flows generally are less permeable and form highly viscous lava on flat topography. The valley-fill deposits and coastal sedimentary deposits on Oahu are hydrologically significant and are discussed below.

Dike-Free Lava Flows.--The permeability of the subaerial, shield-building, dike-free lava flows of Oahu generally is high. The main elements of lava flows contributing to the permeability are (1) clinker zones associated with aa flows, (2) voids along the contacts between flows, (3) cooling joints normal to flow surfaces, and (4) lava tubes associated with pahoehoe flows. The regional hydraulic conductivity of the dike-free lava flows generally 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, water-table gradients in these rocks are small (about 1 ft/mi).

Dikes.--Intrusive volcanic rocks include rocks, such as dikes and sills, that formed by magma that cooled below the ground surface. Dikes associated with the rift zones of the Waianae and Koolau Volcanoes are the dominant intrusive rocks on Oahu, and are most abundant within the central area of the rift zones. Although the thickness of individual dikes generally is less than 10 ft, dikes are hydrologically significant because of their low permeability and their impounding effect on ground water. Ground-water levels in parts of

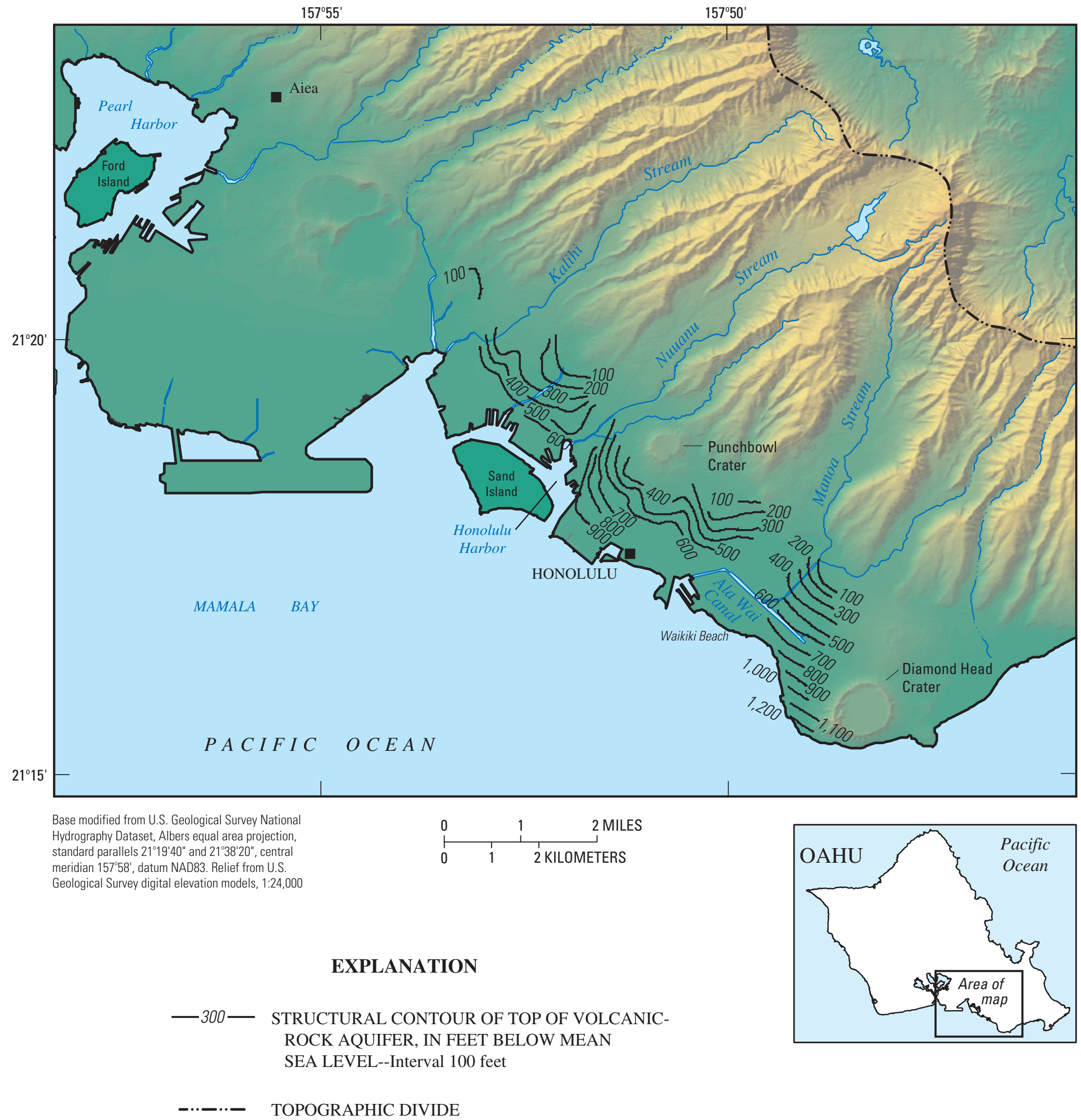


Figure 7. Structural contours of the top of the volcanic-rock aquifer in the Honolulu area, island of Oahu, Hawaii (modified from Palmer, 1927; 1946).

the rift zone of the Koolau Volcano may be as high as 1,000 ft above sea level.

In general, the average hydraulic conductivity of a rift zone decreases as the number of dike intrusions within the rift zone increases. In addition, hydraulic conductivity is expected to be higher in a direction along the strike of the dikes rather than perpendicular to the strike. On the basis of a numerical model analysis, Meyer and Souza (1995) suggested that the average, effective hydraulic conductivity of a dike complex ranges from about 0.01 to 0.1 ft/d. These values reflect the influence of both the intrusive dikes as well as the lava flows between dikes. The hydraulic conductivity of the intrusive dike material was estimated to range from 10^{-5} to 10^{-2} ft/d (Meyer and Souza, 1995).

Weathering.--Weathered volcanic rocks may have a much lower permeability than unweathered volcanic rocks. The reduction of permeability may be attributed to secondary mineralization that clogs the original open spaces, or clays and colloids that precipitate from percolating water (Mink and Lau, 1980). An injection test conducted in weathered basalt beneath Waiawa Stream valley yielded a hydraulic conductivity of 0.058 ft/d (R.M. Towill Corporation, 1978). On the basis of laboratory permeameter tests on core samples, Wentworth (1938) estimated the hydraulic conductivity of weathered basalt to be between 0.083 and 0.128 ft/d. Miller (1987) used the water-retention characteristics of core samples collected beneath pineapple fields of central Oahu to estimate the saturated hydraulic conductivity of saprolite and found values ranging from 0.0028 to 283 ft/d. The wide range of hydraulic-conductivity values estimated by Miller (1987) was attributed to the variability in macroporosity among samples.

Old Alluvium.--Wentworth (1951) classified the sedimentary rocks of Oahu into old, intermediate, and recent alluvial and marine. The sediments of greatest hydrologic significance are the old terrestrial sediments, which were created during the period of extensive erosion that carved deep valleys in the original volcanoes. Old alluvium forms deposits in deeply incised valleys and beneath the coastal plain of Oahu and is hydrologically significant because of its low permeability. The low permeability of old alluvium is caused by a reduction of pore space from the volume increase associated with weathering as well as mechanical compaction (Wentworth, 1951).

Wentworth (1938) estimated the hydraulic conductivity of three weathered alluvium samples with the use of a laboratory permeameter. Two of the samples had a hydraulic conductivity of less than 0.013 ft/d, and the third sample had a hydraulic conductivity of 1.08 ft/d. Eight samples classified as alluvium, without reference to weathering, produced a range of hydraulic conductivity from 0.019 to 0.37 ft/d.

Coastal Sedimentary Deposits.--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. The caprock of southern Oahu includes terrestrial alluvium, marine sediments, calcareous reef deposits, pyroclastic rocks of the Honolulu Volcanics, and highly weathered basalt (Visher and Mink, 1964). In addition, massive aa cores or pahoehoe flows that are located near the coastal discharge zones also may impede the seaward discharge of fresh ground water. Although the permeability of the various components of the coastal caprock may vary widely, from low-permeability old alluvium and saprolite to cavernous limestone deposits, the overall effect of the caprock is one of low permeability (Visher and Mink, 1964). Souza and Voss (1987) modeled a vertical cross section of the Pearl Harbor ground-water area and estimated a caprock hydraulic conductivity of 0.0457 meters per day (0.15 ft/d). In their analysis, Souza and Voss (1987) treated the caprock as a homogeneous and isotropic unit, although significant heterogeneity may exist (Oki and others, 1998).

Soils

Soils are naturally occurring materials that are made up of mineral matter, organic matter, air, and water. Soils form by physical, chemical, and biological processes that involve addition, loss, translocation, and transformation of material. Examples of these processes include addition of organic matter to soils from decaying plants and animals; loss of silica, calcium, magnesium, sodium, or potassium from leaching; translocation or movement of clay minerals to lower horizons; and chemical transformation of primary rock minerals to clay minerals and iron and aluminum oxides.

The Natural Resources Conservation Service (NRCS) has identified 12 soil orders or major soil types (U.S. Department of Agriculture, 1998). Of these 12 soil orders, 11 have been reported in Hawaii, and 9 are found on Oahu (Gavenda and others, 1998). On the basis of mapped soil series (U.S. Department of Agriculture, 2001b; Foote and others, 1972) and NRCS soil series descriptions (U.S. Department of Agriculture, 2001a), the soil orders found on Oahu are Oxisols, Ultisols, Mollisols, Vertisols, Entisols, Inceptisols, Andisols, Histosols, and Aridisols (fig. 8). However, Gavenda and others (1998) indicate the presence of Alfisols but no Aridisols on Oahu.

Oxisols are highly weathered soils that consist mainly of kaolinitic clay minerals and iron and aluminum oxides, and have a low cation exchange capacity. Oxisols developed mainly on lava flows and alluvium, and form much of the red agricultural soils of central Oahu. Ultisols are highly weathered soils that generally have an argillic (high clay content) horizon in the subsoil formed by translocation of clays from higher in the profile. Ultisols developed mainly on lava flows and alluvium, and are found in windward Oahu and slopes of central Oahu. Oxisols and Ultisols containing variably charged iron and aluminum oxide particles have a large capacity to adsorb nitrate under low pH conditions (Uehara, 1996; Deenik, 1997; Uehara and Gillman, 1981). Mollisols are relatively young soils that commonly developed over limestone and alluvium in coastal areas of Oahu. Vertisols contain clay minerals (montmorillonite) that cause the soil to shrink and swell with changes in water content, and typically developed on colluvium or alluvium. Entisols are recent soils that have little or no horizon development and that are little changed from the parent material in which they developed. Much of the mountainous rocky lands of the Koolau Range have been classified as Entisols by Gavenda and others (1998). Inceptisols have weakly developed soil horizons and are commonly older than Entisols. Andisols developed on deposits associated with the rejuvenated-stage Honolulu Volcanics in southeastern Oahu. Histosols are soils with high organic content, and generally are found in poorly drained bog areas on Oahu. Aridisols are soils that developed in arid climates, and are found in dry coastal areas of Oahu. Like Ultisols, Alfisols have an accumulation of clays in the subsoil. Alfisols are less weathered than Ultisols and contain higher concentrations of nutrients.

The main factors that affect the characteristics of a soil include climate, biological activity, parent material, topography, and time. Climatic gradients on Oahu are steep, and this affects the spatial distribution of soils (fig. 8). In some areas, soil formation may be related more to past, rather than present, climatic conditions (Gavenda, 1992). In general, the concentration of kaolinite decreases and concentrations of aluminum and iron oxides increase with increasing rainfall (see for example Tamura and others, 1953). Highly weathered soils like Ultisols generally are found in wetter areas, whereas Aridisols are found only in dry areas. Vegetation and organic matter also generally increase with increasing rainfall. Parent-rock materials on Oahu are primarily volcanic in origin, and may be associated with lava flows from which residual soils develop, or may be from transported materials including alluvium, colluvium, and ash. In coastal areas, parent material may be from limestone, which can lead to a soil with different chemical and physical properties than soils developed from volcanic parent material. Topography also affects the character of the soil. For example, soils on steep slopes are commonly thin because of erosion. In geologically young areas, soils may not have developed yet because the soil-forming processes have not had sufficient time to be effective.

Hawaiian soils also may contain material from atmospheric inputs. Wind-blown dust from Asia can result in accumulation of minerals such as quartz, a mineral generally absent from the volcanic rocks on Oahu (Kurtz and others, 2001). In addition, phosphorus added to soils as wind-blown dust minerals can be released by chemical weathering and made bioavailable (Kurtz and others, 2001). Phosphate, which may be added to soils as a fertilizer, is retained by goethite and other iron and aluminum oxides and hydroxides (Parfitt and others, 1975; Fox and Searle, 1978; McLaughlin and others, 1981; Barron and others, 1988) that are common in Hawaiian soils.

Soils that are used for agriculture on Oahu generally can transmit water downward at rates of a few inches per hour, although the rates can range from less than 0.06 to 20 in/hr (Foote and others, 1972). The infiltration capacity of agricultural soils can be reduced by urbanization. Murabayashi and Fok (1979) used double-ring infiltrometers to quantify the effects of urbanization on the constant infiltration rate and estimated that urbanization can reduce the constant infiltration rate by 83 percent. Wood (1971) indicated that

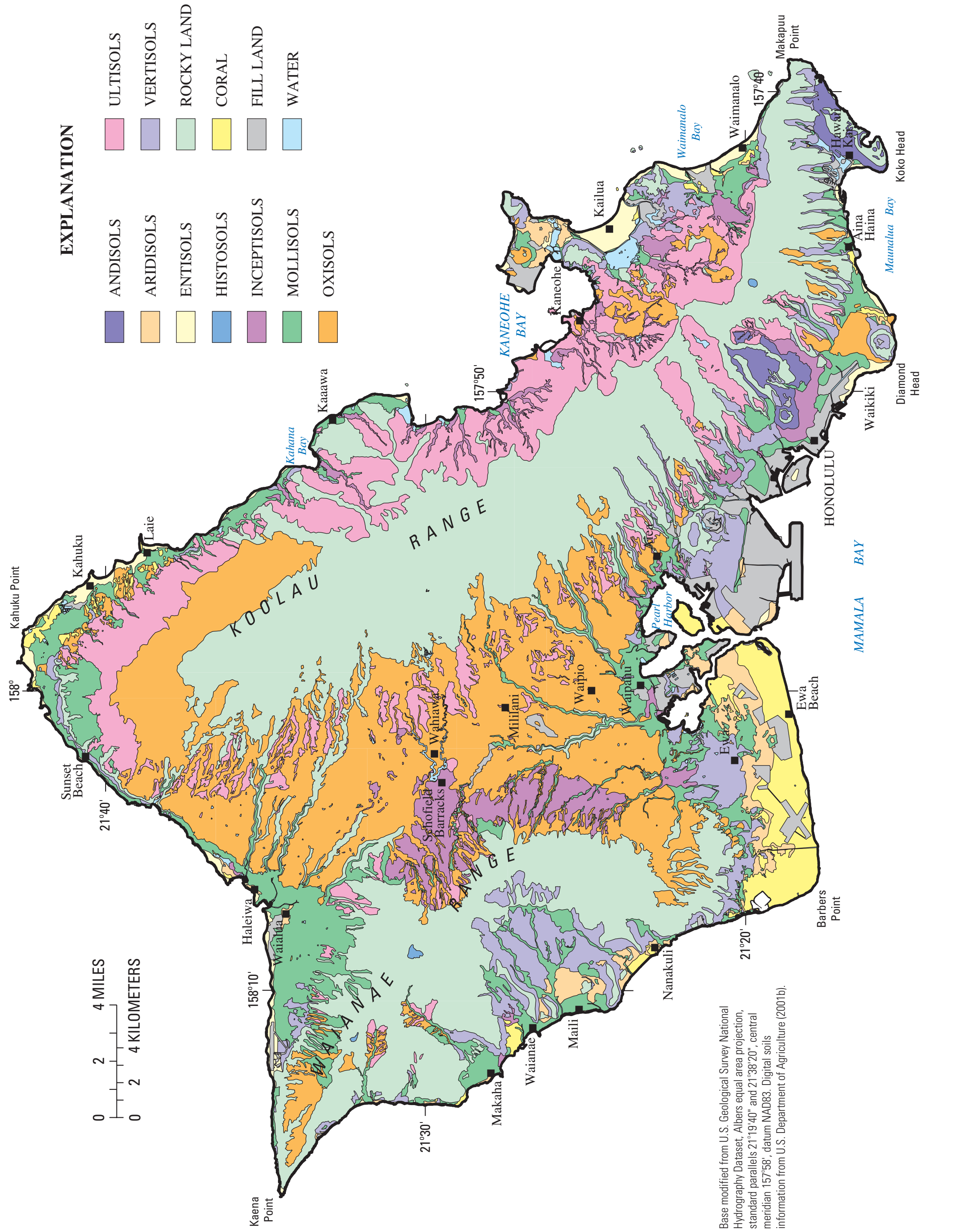


Figure 8. Soil orders, island of Oahu, Hawaii (modified from U.S. Department of Agriculture, 2001b; Foote and others, 1972).

hydrologic characteristics of soils on Oahu varied with land use. In general, infiltration rates in forested areas were higher than in adjacent areas with the same soil types used for sugarcane, pineapples, or pasture (Wood, 1971).

Surface Water

The Waianae and Koolau Ranges have been deeply dissected by numerous streams with main courses that generally have followed the consequent drainage pattern on the original volcanoes. Numerous tributaries commonly join the main stream. Some stream courses have been modified by the presence of rejuvenated-stage volcanic rocks. For example, the course of Manoa Stream was shifted eastward because of lava flows of the Honolulu Volcanics in Manoa Stream valley (Wentworth, 1951; Macdonald and others, 1983). Streams originate in the mountainous interiors of the Waianae and Koolau Ranges and terminate at the coast (fig. 1). Some of these streams flow perennially throughout their entire course, others flow perennially over parts of their course, and the remaining streams flow during only parts of the year throughout their entire course. A total of 57 streams on Oahu have been classified as perennial in all or part of their courses (Hawaii Cooperative Park Service Unit, 1990). Streams commonly flow perennially in the interior, dike-intruded areas, where the ground-water table is intersected and where rainfall is persistent, or near the coast, where the water table is higher than the steam level.

Descriptions of the surface-water resources and flow characteristics associated with Oahu's streams include those for the windward (Hirashima, 1962, 1963, 1965; Takasaki and others, 1969), north-central (Rosenau and others, 1971), northern (Takasaki and Valenciano, 1969), southeastern (Takasaki and Mink, 1982), and southern (Mink, 1962; Hirashima, 1971; Shade, 1984) parts of the island. In general, drainage basins on Oahu are small and streams are flashy. However, streamflow characteristics are highly variable, both spatially and temporally.

Drainage-Basin Characteristics

Drainage basins on Oahu are generally small and have steep sides. Drainage basins are small mainly because the distance between the headwaters and mouths of streams is short and adjacent streams are closely spaced. Furthermore, the topography associated with Hawaiian shield volcanoes leads to an initial drainage pattern in which streams flow away from each other, rather than into each other as in most continental settings. In most of the windward area, drainage basins generally are smaller, shorter, and wider than those in central Oahu, and drainage basins in the Honolulu area are intermediate in size and shape. The largest basins drain the saddle area of central Oahu and can exceed 45 mi^2 (Wong, 1994). The main streams draining the central saddle follow a curved path from their headwaters in the Koolau Range to the coast.

Drainage-basin divides are clearly defined where formed by steep-sided ridges near the mountainous interior areas. In some interior areas, the stream channel may be more than a thousand feet below the adjacent ridgeline that forms the basin divide. Drainage-basin divides are less well defined in the flatter coastal areas. In the saddle area of central Oahu, basin divides are on broad interfluves that separate V-shaped gulches. Surface-drainage divides on Oahu are not coincident with ground-water divides (see for example Hirashima, 1963), although they may be similar in some places.

Streambed slopes are steep in the mountainous interior, where rainfall is high, and flatter near the coast. In the interior areas of the Koolau Range, within 0.5 mi of the topographic crest, slopes generally are greater than 20 percent and can exceed 50 percent in places. Near the coast, below an altitude of 100 ft, streambed slopes generally are less than a few percent.

The interior parts of most drainage basins are in the dike complex or marginal dike zone. In many basins, particularly those in windward Oahu, dikes have been exposed by erosion. The coastal parts of drainage basins generally are covered with marine and terrestrial sediments. Geohydrologic conditions are an important factor controlling interactions between ground water and surface water and are described in the section of this report titled "Interaction of Ground Water and Surface Water."

Streamflow Characteristics

Streamflow consists of (1) direct runoff of rainfall, in the form of overland flow and subsurface storm flow that rapidly returns infiltrated water to the stream, (2) ground-water discharge, in the form of base flow, where the stream intersects the water table, (3) water returned from bank storage, (4) rain that falls directly on streams, and (5) any additional water, including excess irrigation water, discharged to the stream by humans. The amount of direct runoff and base flow that contributes to total streamflow is dependent on factors including rainfall amount and intensity, drainage-basin geology, morphology, and size, soils, and land cover. Humans can affect streamflow characteristics through diversions, channelization, dams, land-use changes, and other factors.

For 1980's land-use conditions on the island of Oahu, Shade and Nichols (1996) estimated that about 329 Mgal/d, or 17 percent of the islandwide annual rainfall, flows to the ocean as direct runoff. However, the ratio of runoff to rainfall varies by basin and even within a basin (Shade and Nichols, 1996; Rosenau and others, 1971; Mink, 1962; Hirashima, 1971). Within a basin, the ratio of runoff to rainfall may vary depending on antecedent soil-moisture conditions, the distribution, amount, and intensity of rainfall, and land cover (Anderson and others, 1966; Giambelluca, 1983; Shade, 1984). For example, in the Moanalua Stream valley, the ratio of runoff to rainfall on an event basis may range from less than 0.1 to greater than 0.5 (Shade, 1984). The ratio of runoff to rainfall in a basin generally increases with increasing antecedent soil moisture, increasing rainfall amount and intensity, and decreasing permeability of the land surface associated with land-use or vegetation changes.

Streams in the Oahu Study Unit are flashy because of high-intensity rainfall, small drainage-basin size, steep basin and stream slopes, and little channel storage (Wong, 1994). Stream stage commonly rises and falls several feet over a few hours in response to rainfall. The flood hydrograph for a single storm typically has a sharp rise and a steep recession, and can be characterized as having a steep triangular shape and short time to peak (fig. 9) (Wu, 1969).

On the basis of 2,317 recorded annual peak-discharge measurements for Oahu with known dates, Wong (1994) estimated that 89 percent of the peaks occurred between October and May. This period corresponds to the rainy season, during which heavy storms and flooding may occur. A multiple-regression analysis (Wong, 1994) indicated that the 2-, 5-, 10-, 25-, 50-, and 100-year peak discharges on Oahu were significantly correlated with drainage area, and in some areas, median annual rainfall or the 2-year, 24-hour rainfall intensity. The bedload (the part of sediment load that moves by rolling, slipping, or sliding along the streambed) and suspended-sediment load of a stream can be significant during periods of flood flows.

On a daily time scale, stream discharge varies spatially and temporally depending on factors including rainfall, basin characteristics, and streamflow regulation (fig. 9). The timing and magnitude of peaks in the streamflow hydrographs for different sites reflect spatial differences in rainfall amount, intensity, and timing as well as differences in basin characteristics, including size, slopes, land cover, soil types, and geohydrologic conditions. During dry periods, the low-flow characteristics of a stream may be dependent on ground-water inflow. Surface-water diversions, ground-water withdrawals near streams, or wastewater input to the stream may affect the low-flow characteristics of the stream.

A flow-duration curve for daily mean discharges is a cumulative-frequency curve that shows the percentage of days specified discharges were equaled or exceeded during a given time period. Flow-duration curves provide an indication of streamflow variability and availability. Flow-duration curves for streams with a large and persistent component of ground-water inflow generally are flatter than those for streams that have little or no ground-water inflow and, thus, more variable flow rates. Because streams in windward Oahu commonly receive significant ground-water inflow, flow-duration curves of daily discharge for streams in windward Oahu generally are less variable (flatter) for low flows than curves for streams in leeward Oahu (fig. 10).

Seasonal streamflow patterns are spatially variable. In some areas, monthly streamflow is higher during the wet season than the dry season (fig. 11). In other areas, particularly where base flow is significant and rainfall is persistent, seasonal streamflow variations are less pronounced (fig. 11).

Discharge at a site varies from year to year depending mainly on rainfall (fig. 12). Prolonged periods of less than average rainfall may cause periods of less than average streamflow at a site. Upstream surface-water diversions or nearby ground-water withdrawals that reduce base flow also can cause periods of less than average streamflow.

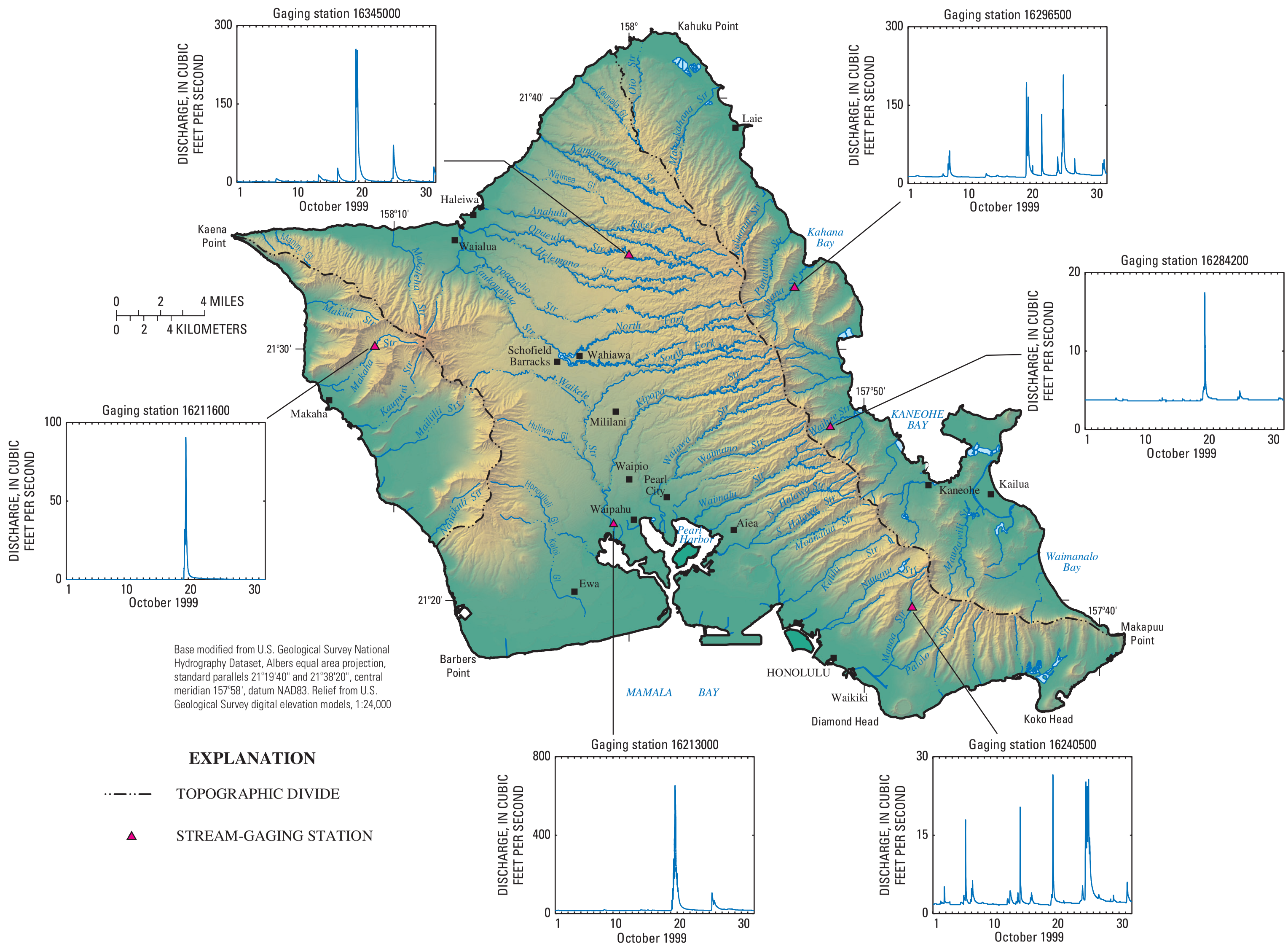


Figure 9. Stream discharge during October 1999 at selected stream-gaging stations, island of Oahu, Hawaii.

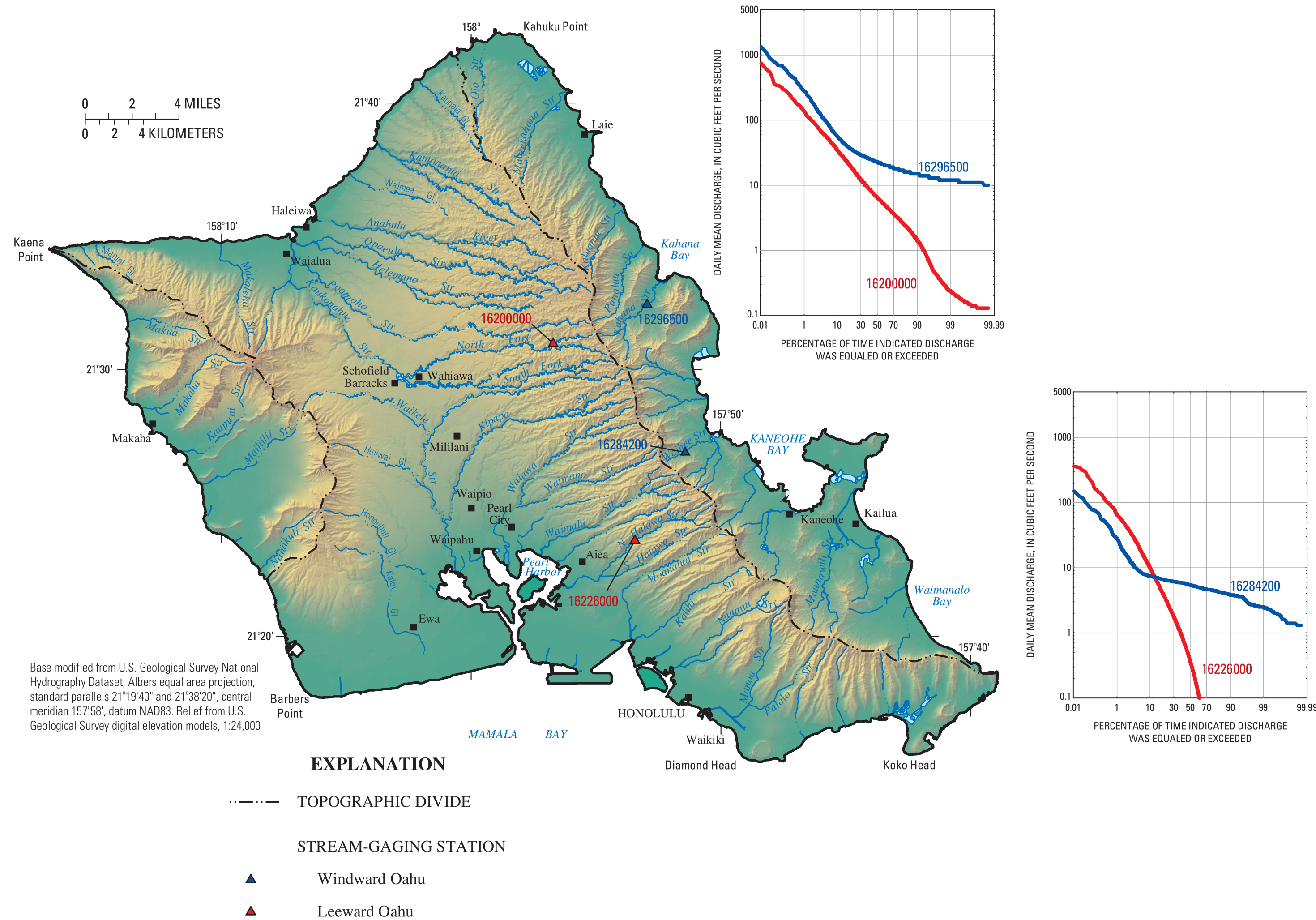


Figure 10. Flow-duration curves for water years 1975–2000 for selected stream-gaging stations, island of Oahu, Hawaii. (A water year begins in October of the preceding year and ends in September.)

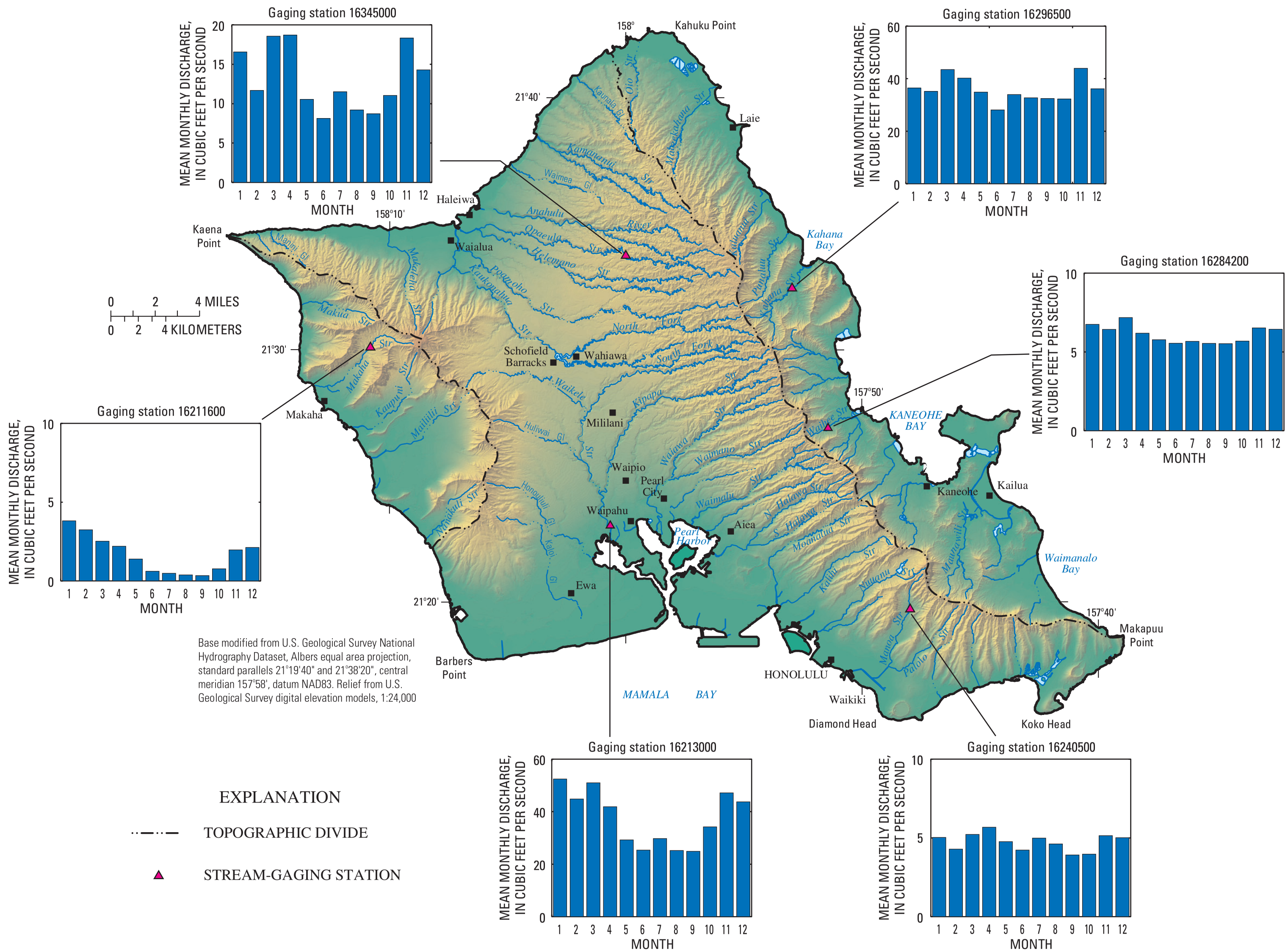


Figure 11. Mean monthly discharge during water years 1975–2000 at selected stream-gaging stations, island of Oahu, Hawaii. (A water year begins in October of the preceding year and ends in September.)

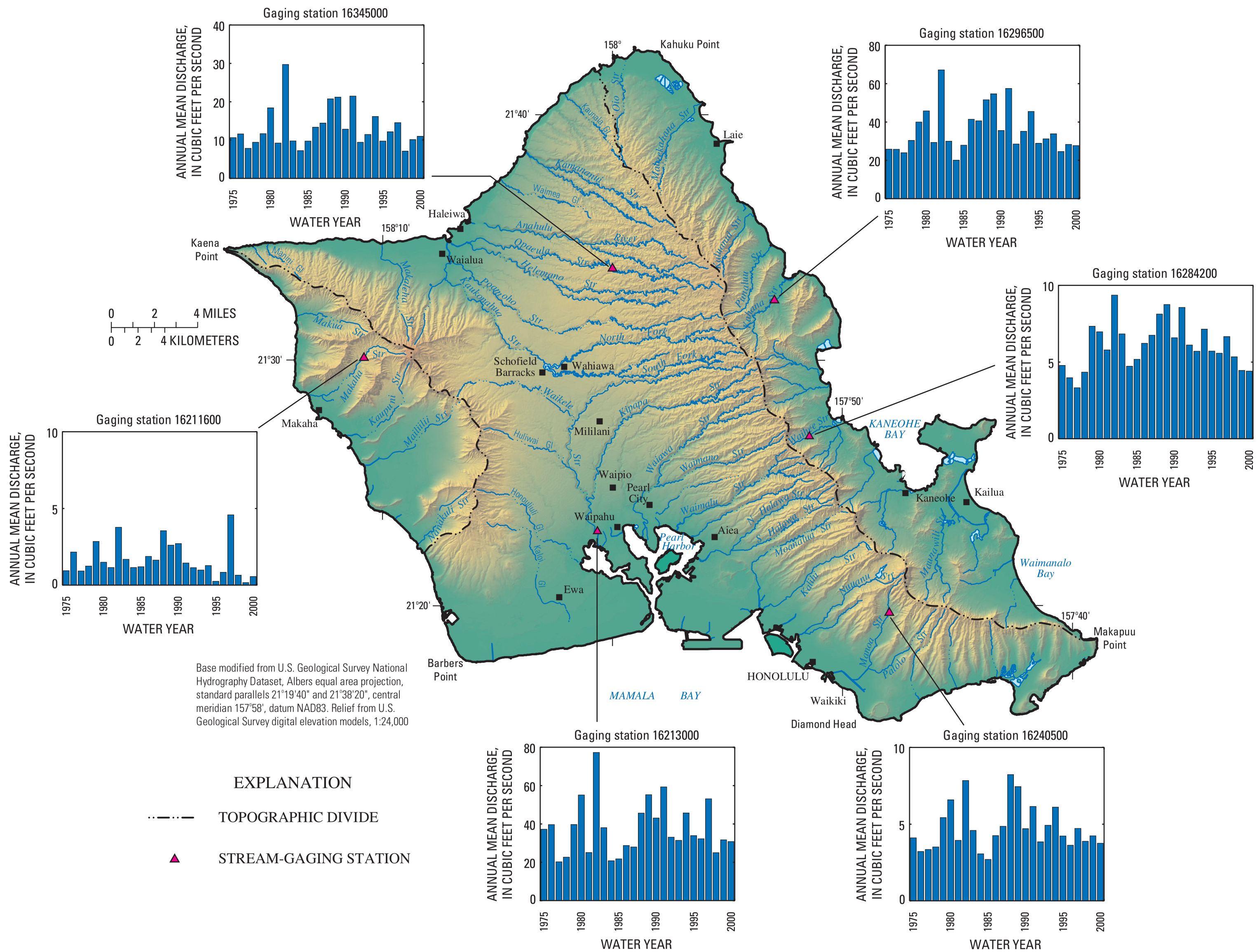


Figure 12. Annual mean discharge during water years 1975–2000 at selected stream-gaging stations, island of Oahu, Hawaii. (A water year begins in October of the preceding year and ends in September.)

Ground Water

On Oahu, ground water is the source of almost all of the domestic water. Ground water also was used extensively in the past for irrigation of sugarcane, although sugarcane is no longer cultivated on Oahu. The main source of recharge to the ground-water system on Oahu is rainfall. Stream losses, irrigation water that percolates past the plant root zone (Giambelluca, 1983; Eyre, 1983), fog drip at high altitudes in the Koolau Range (Ekern, 1983), wastewater from cesspools and septic tanks, and leaks from underground pipelines also may contribute to ground-water recharge. For mid-1980's land-use conditions, Shade and Nichols (1996) estimated total recharge on Oahu to be 880 Mgal/d, which represents about 45 percent of the total rainfall on Oahu. The spatial distribution of recharge on Oahu reflects the rainfall and land-use distributions. Recharge may exceed 150 in/yr in the high-rainfall areas of the Koolau Range, and generally is less than 10 in/yr near the coast (Shade and Nichols, 1996). Irrigation water commonly enhances recharge derived from rainfall in agricultural areas.

Volcanic rocks make up most of Oahu and compose the most important aquifers. Quaternary-age consolidated sedimentary deposits, which are principally coralline limestone, form productive aquifers in coastal areas but generally contain brackish water or saltwater. The hydraulic properties of the rocks control the modes of ground-water occurrence on Oahu. In general, the dike-free volcanic rocks on Oahu are highly permeable. However, low-permeability intrusive dikes, marine and terrestrial coastal sediments, massive lava flows, valley-filling old alluvium, and weathered volcanic rocks can have a significant effect on the ground-water system by impeding flow. On Oahu, fresh ground water is found mainly in freshwater-lens systems and dike-impounded systems, with much smaller amounts in perched systems. Ground water in the Schofield area of central Oahu is impounded by geologic structures of uncertain origin.

Freshwater-Lens Systems

A freshwater-lens system includes a lens-shaped freshwater body, an intermediate transition zone of brackish water, and underlying saltwater (fig. 13). Freshwater-lens systems are found in dike-free volcanic rocks and sedimentary deposits under confined or unconfined conditions. Water levels in the freshwater-lens systems of Oahu generally range from a few feet to a few tens of feet above sea level (Hunt, 1996). The most important sources of ground water on Oahu are from the freshwater parts of these systems in Honolulu and central Oahu, where the freshwater body is hundreds of feet thick in places. The transition zone can be quite thick (several tens to hundreds of feet) depending on the extent of mixing between freshwater and saltwater (see for example, Oki, 1998). The thicknesses of the freshwater and transition zones are monitored by collecting vertical profiles of fluid electrical conductivity, which is an indicator of salinity, from deep wells that are open to the aquifer in the freshwater and transition zones (fig. 14).

Freshwater-lens systems are recharged mainly by direct infiltration of precipitation and irrigation water, and by inflow from upgradient ground-water systems. Discharge from freshwater-lens systems on Oahu mainly is by diffuse seepage near the coast and to subaerial and submarine coastal springs. A caprock confining unit generally impedes the discharge of freshwater from these systems, and causes the freshwater lens to be thicker than it would be without confinement (Visher and Mink, 1964). Salinity of ground water in the caprock is variable (Oki and others, 1998) and this water is considered part of the freshwater-lens system.

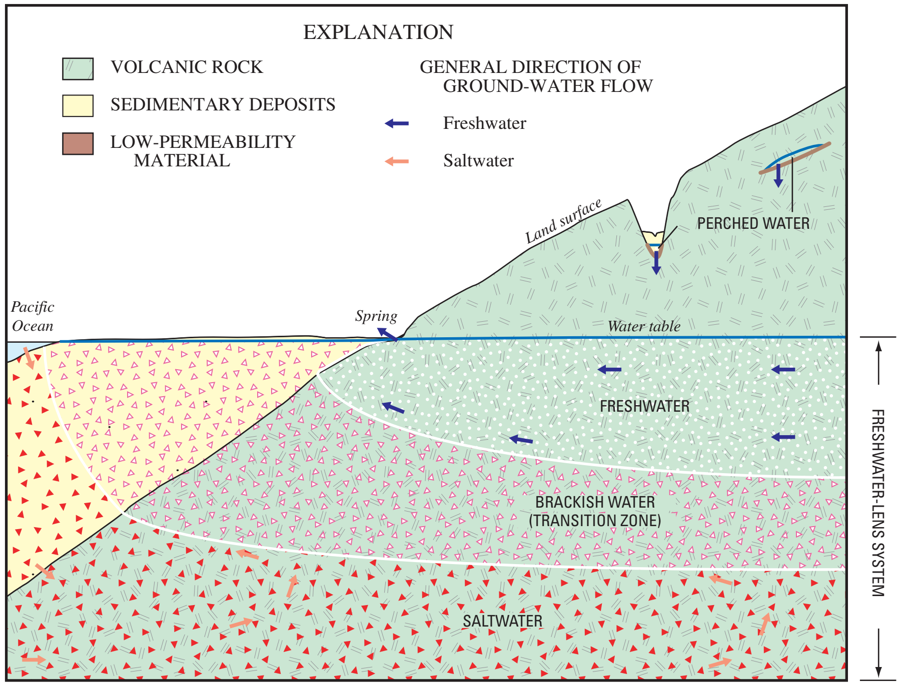
Dike-Impounded Systems

A dike-impounded system is found in the rift zones and caldera area of a volcano where low-permeability dikes have intruded other rocks. The flow system includes the freshwater body and, where it exists, the underlying brackish water and saltwater (fig. 13). Near-vertical dikes tend to compartmentalize areas of permeable volcanic rocks. Dikes impound water to heights of at least 1,000 ft above sea level in the rift zone of the Koolau Volcano (Takasaki and Mink, 1985). In windward Oahu, tunnels have been used to develop dike-impounded water.

The depth to which freshwater extends below sea level within a dike-impounded system is not known in places with high water tables, although freshwater probably extends far below sea level. Where few dikes intrude permeable volcanic rocks, the water table may be only a few feet to a few tens of feet above sea level and brackish water has been found below the freshwater.

Dike-impounded systems are recharged mainly by direct infiltration of precipitation. Where erosion

A



B

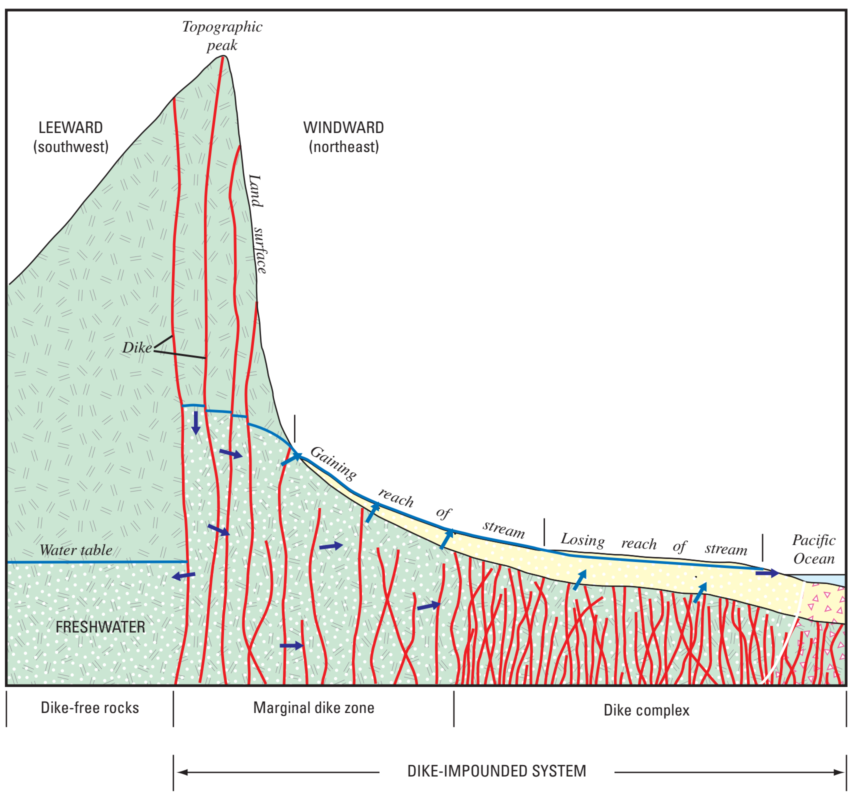


Figure 13. Schematic cross sections showing (***A***) freshwater-lens system and perched water, and (***B***) dike-impounded system (modified from Takasaki and Mink, 1985).

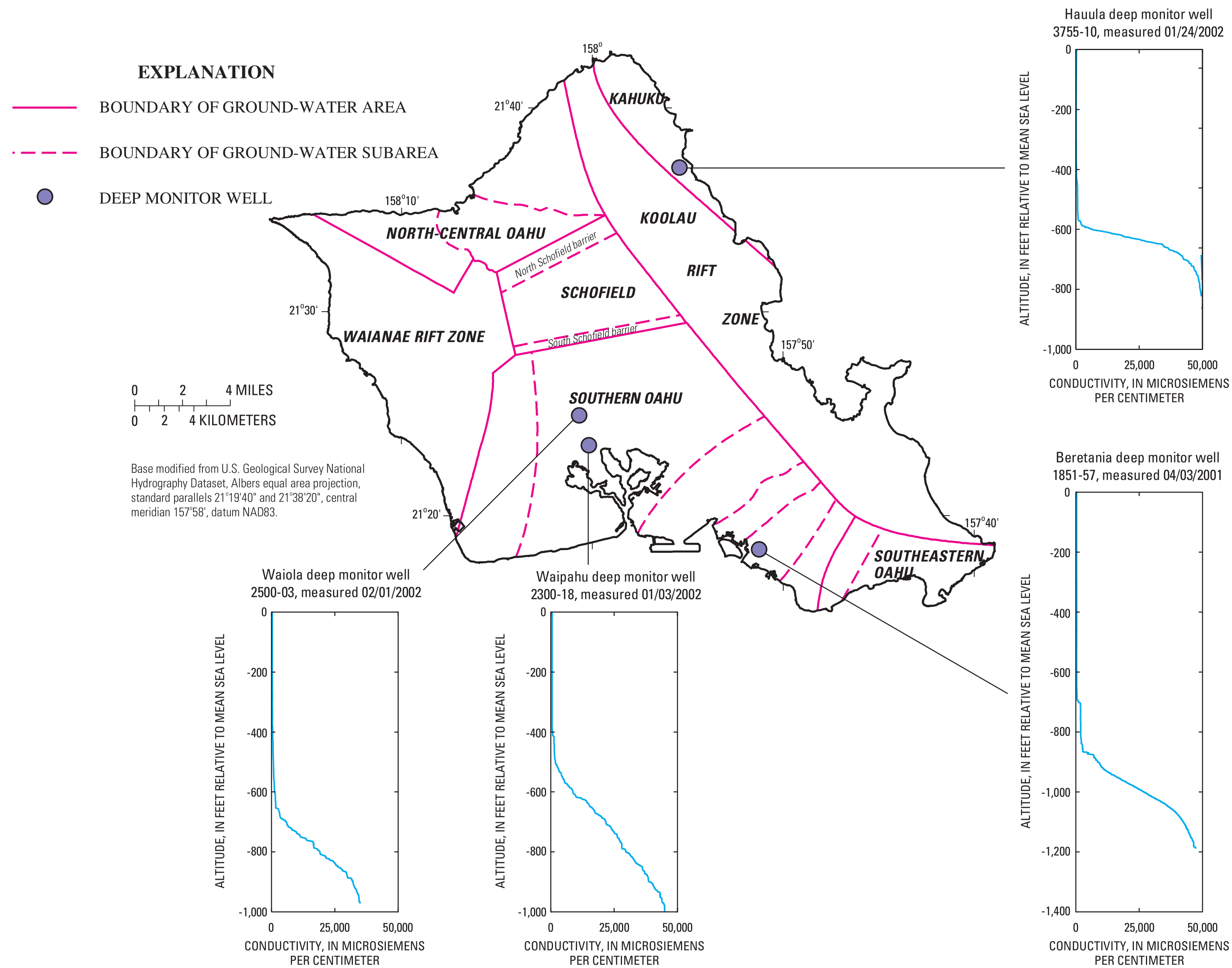


Figure 14. Fluid-conductivity profiles from selected deep monitor wells, island of Oahu, Hawaii. Conductivity-profile data provided by Honolulu Board of Water Supply.

has exposed dike compartments in stream valleys, such as in windward Oahu, ground water can discharge directly to streams. In other areas, fresh ground water in dike-impounded systems can discharge to downgradient ground-water systems or directly to the ocean. A caprock confining unit commonly impedes the discharge of freshwater from dike-impounded systems to the ocean.

Perched Systems

Perched water is found in areas where low-permeability rocks impede the downward movement of ground water sufficiently to allow a perched water body to develop within otherwise unsaturated rocks (fig. 13). These low-permeability rocks may include massive, thick-bedded lava flows, buried soil and weathered ash layers, and sedimentary deposits. On Oahu, perched systems have been reported to exist in valley-filling deposits in the Honolulu area (Wentworth, 1951) and in the saprolite of central Oahu (State of Hawaii, 1983), but generally are not developed as a resource. The extent of the perched system depends on the areal extent of the low-permeability rocks. The height of the water table above sea level in a perched system depends on the altitude of the low-permeability rocks and the rate and duration of recharge. Discharge from a perched system responds to variations in recharge and can be to springs, streams, downward to a lower water table, or to the atmosphere by evapotranspiration. In some areas, perched water may exist following periods of heavy rainfall, but the rocks may later become unsaturated during an extended dry period.

Ground-Water Areas

The Koolau Basalt is overall the most important aquifer on Oahu, although the Waianae Volcanics forms the most important aquifer in western Oahu. Younger Koolau Basalt overlies Waianae Volcanics in the western part of central Oahu. The two aquifers are separated by a confining unit formed by soil and saprolite material of low permeability on the surface of the Waianae Volcano that was buried by Koolau Basalt. This confining unit is referred to as the Waianae confining bed (Hunt, 1996). Hunt (1996) divided the island of Oahu into seven major ground-water areas, primarily on the basis of geologic or hydrologic differences (fig. 15). Each major area contains one or both of the two main volcanic-rock aquifers.

Dike-impounded systems exist in the Waianae and Koolau rift zones. Freshwater-lens systems exist in the southern, southeastern, north-central, and Kahuku ground-water areas. The Schofield area of central Oahu is hydrologically connected to adjacent freshwater-lens and dike-impounded systems, but the ground water in the Schofield area may be neither a freshwater-lens nor a dike-impounded system.

Ground water moves from areas of higher water levels to areas of lower water levels, which generally corresponds to flow from inland, rift-zone areas toward the ocean. Ground-water levels on Oahu are highest in the rift zones where recharge is high and the regional permeability is low. Water levels in the Waianae and Koolau rift zones, respectively, are as high as 1,600 and 1,000 ft above sea level. Ground water in the rift zones discharges to streams, the ocean, or to adjacent, downgradient ground-water areas.

The Schofield ground-water area is formed mainly by Koolau Basalt, although Waianae Volcanics is present in the western part. Ground-water levels in the Schofield area are about 275 ft above sea level (Dale and Takasaki, 1976), which is considerably higher than the water levels of up to a few tens of feet in the adjacent freshwater-lens systems to the north and south. The Schofield area is separated from adjacent freshwater-lens systems to the north and south by low-permeability features that may be related to dikes or buried ridges, although the geologic origin of these barriers is not fully understood. These barriers are commonly referred to as ground-water dams (Dale and Takasaki, 1976). Water levels within the barrier areas range from about 130 to 275 ft above sea level and are transitional between the Schofield area and the adjacent freshwater-lens systems. The Schofield ground-water area receives recharge from the adjacent Koolau and Waianae rift zones; the water that is not withdrawn from wells then flows to the north or south across the northern and southern Schofield ground-water barriers, and recharges the freshwater-lens system in the north-central and southern ground-water areas (Oki, 1998).

The north-central Oahu ground-water area can be divided into the Mokuleia, Waialua, and Kawailoa subareas (named from west to east) (Hunt, 1996). The Waianae confining bed separates the Mokuleia subarea (Waianae Volcanics) and Waialua subarea (Koolau Basalt), and the low-permeability valley-filling deposits and underlying weathered rock associated with the

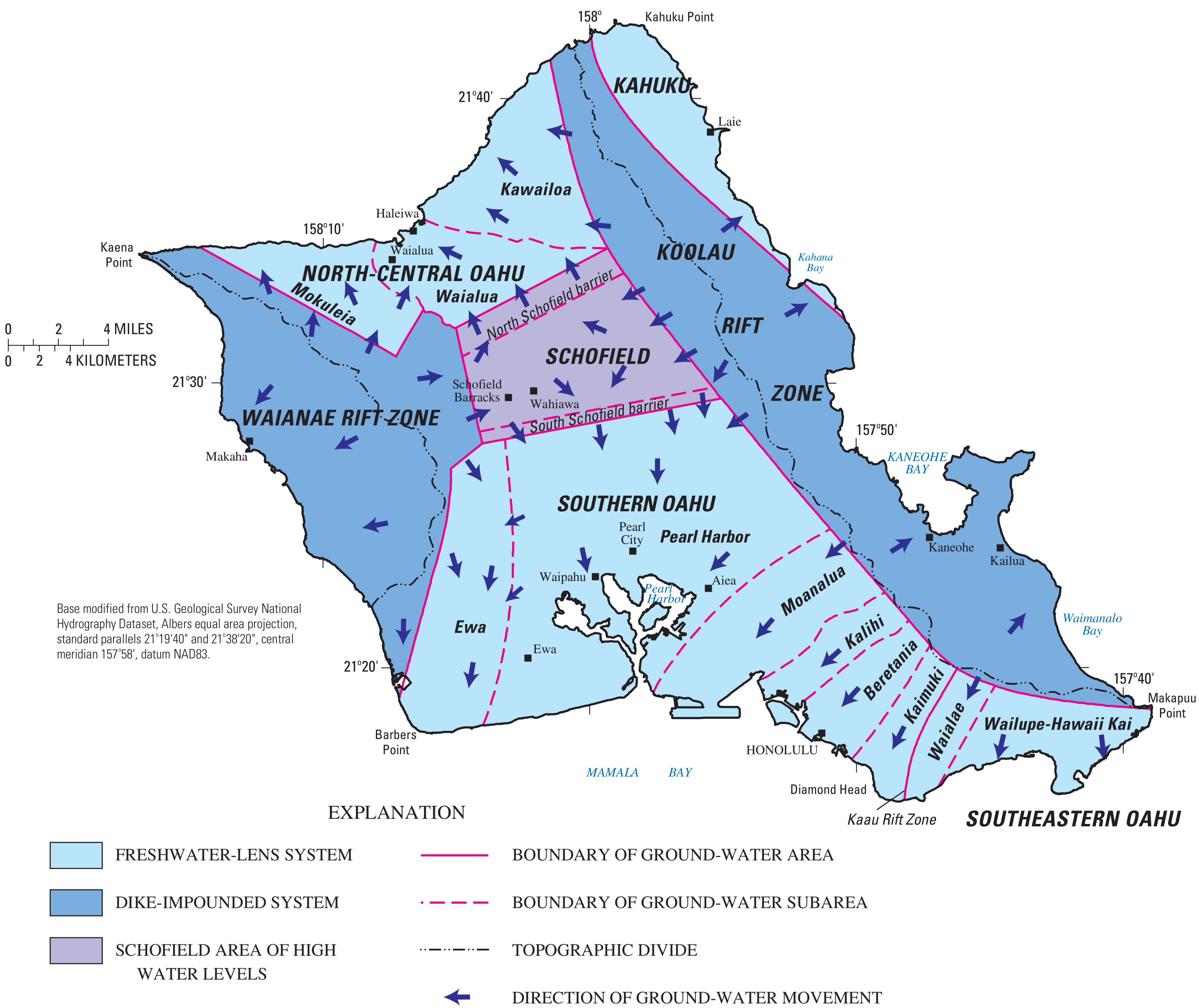


Figure 15. Ground-water areas and generalized directions of ground-water movement, island of Oahu, Hawaii (modified from Hunt, 1996).

Anahulu River gulch separate the Waialua and Kawailoa subareas. Water levels in the freshwater lens of the north-central ground-water area are highest in the southwestern part where the aquifer is formed by Waianae Volcanics and the caprock is thick, and lowest nearshore in the northern part where the aquifer is formed by Koolau Basalt and the caprock is thin. Measured water levels on opposite sides of the Waianae confining bed are about 15 to 25 ft above sea level in the Mokuleia subarea and 10 to 12 ft above sea level in the Waialua subarea (Hunt, 1996; Oki, 1998). Measured water levels on opposite sides of the Anahulu Gulch barrier are about 10 to 12 ft above sea level to the south in the Waialua subarea and 3 to 7 ft above sea level to the north in the Kawailoa subarea (Hunt, 1996; Oki, 1998). The regional ground-water movement is from adjacent areas of dike-impounded water and the Schofield ground-water area northward and northwestward to the ocean, although some water may flow eastward across the Waianae confining bed and northward across the Anahulu Gulch barrier.

The southern Oahu ground-water area can be divided into the Ewa, Pearl Harbor, Moanalua, Kalihi, Beretania, and Kaimuki subareas (named from west to east) (Hunt, 1996). The Waianae confining bed separates the Ewa subarea (Waianae Volcanics) and Pearl Harbor subarea (Koolau Basalt). Within the Koolau Basalt, the low permeability valley-filling deposits and underlying weathered rock associated with Halawa, Kalihi, Nuuanu, and Manoa Stream valleys separate adjacent subareas. Measured water levels at comparable distances from the coast generally are highest in the Beretania and Kalihi subareas and decrease to the east and west. Water levels in the southern Oahu ground-water area generally range from about 25 to 30 ft above sea level inland to about 15 to 25 ft above sea level near the coast (Hunt, 1996; Oki, 1998). In the southern Oahu ground-water area, the regional ground-water movement is from adjacent areas of dike-impounded water and the Schofield ground-water area southward to the ocean. The low-altitude springs near the inland margin of Pearl Harbor, known as the Pearl Harbor springs, are significant ground-water discharge sites (Visher and Mink, 1964; Oki, 1998). Some water in the southern Oahu ground-water area may discharge eastward across the Kaau rift-zone boundary, or westward into the Waianae rift zone area at low altitudes.

The southeastern Oahu ground-water area is bounded by the Koolau rift zone on the north and the ocean on the south. The southern and southeastern Oahu ground-water areas are separated by the Kaau rift zone, although the valley-filling deposits and underlying weathered rock associated with Palolo Stream valley also may contribute to the barrier separating these two areas. Measured water levels in the southern Oahu ground-water area are about 10 to 20 ft higher than those in the southeastern area on the opposite side of the barrier. In the southeastern Oahu ground-water area, water levels generally are less than 10 ft above sea level near the western boundary and decrease eastward. The southeastern Oahu ground-water area can be divided into the Waialae and Wailupe-Hawaii Kai subareas in the west and east, respectively, by a zone of northeast-trending dikes (Takasaki and Mink, 1982). Measured water levels in the Waialae subarea are about 6 to 8 ft higher than in the Wailupe-Hawaii Kai subarea to the east (Takasaki and Mink, 1982; Hunt, 1996). In the southeastern Oahu ground-water area, the regional ground-water movement is from the Koolau rift zone southward to the ocean.

The Kahuku ground-water area of windward Oahu is bounded on the southwest by the Koolau rift zone and on the northeast by the ocean. Measured water levels range from about 20 ft above sea level inland to less than 10 ft above sea level near the coast, and generally are higher in the south than the north (Takasaki and Valenciano, 1969; Hunt, 1996).

Interaction of Ground Water and Surface Water

Intermittent and perennial streams in Hawaii may gain water along some reaches and lose water along other reaches depending on local geohydrologic conditions (see for example Hirashima, 1965; Takasaki and others, 1969; Takasaki and Mink, 1982; Izuka, 1992). Where the streambed is above the water table, the stream can lose water. For example, Hirashima (1971) estimated that Kipapa Stream loses about 0.04 Mgal/d per mile of stream for dry-weather conditions. Some streams do not flow continuously to the coast because water infiltrates into the streambed before reaching the coast. Where the stream intersects the ground-water table, the stream can either gain or lose water, depending on whether the hydraulic head in the adjacent ground-water body is respectively greater than or less than the water level in the stream. The hydraulic properties of the rocks near the stream can affect the rate of flow between the stream and ground-water body.

Where stream channels are lined with concrete, interaction between ground water and surface water is unlikely.

Streams on Oahu flow perennially mainly because of ground-water discharge. In the upper reaches of some streams, persistent orographic rainfall may maintain streamflow during much of the year, although periods of no flow may occur. In some areas, including Honolulu, central Oahu, and the northern part of windward Oahu, streams may be dry below the area of high rainfall because flow is lost to the streambed by infiltration and may ultimately recharge the ground-water body.

The upper reaches of most streams are within or near the area where dikes impound ground water to high levels. Streams that intersect the water table of the dike-impounded ground-water body, including Kahaluu Stream (Hirashima, 1962; 1963) and Waihee Stream (Hirashima, 1965) in windward Oahu, commonly are perennial because they gain water from the dike-impounded ground-water body. However, some streams may lose water to the dike-impounded water body where erosion has not lowered the streams to the water table (Takasaki and Valenciano, 1969). In windward Oahu, dike-impounded water generally is unconfined above an altitude of about 600 ft, where streams can gain water directly from the adjacent volcanic rocks. Sedimentary deposits and weathered volcanic rocks may confine the dike-impounded water at lower altitudes, where streams can gain water by ground-water discharge from the underlying volcanic rocks through the sedimentary deposits (fig. 13). In the Honolulu and central Oahu areas, the upper reaches of some streams also may gain water from the dike-impounded water body.

Although dikes are present near much of the windward Oahu coast, the coastal areas of Honolulu and central Oahu generally are dike free. Some streams in central Oahu, such as Waikele Stream (Hirashima, 1971), flow perennially below an altitude of about 20 ft because the stream intersects the water table of the freshwater-lens system in dike-free volcanic rocks. The water table in the sedimentary deposits near the coast of Honolulu and central Oahu generally is only a few feet above sea level, and thus, ground water in the coastal sedimentary deposits may contribute to streamflow at altitudes below a few feet where the water table is above the water level in the stream.

Factors that affect water levels in streams and ground-water bodies can control the interaction between surface water and ground water. These factors include rainfall, irrigation, ground-water withdrawals, and tides. Rainfall may cause otherwise dry streams to flow, which can lead to discharge from a stream to an underlying ground-water body. Prolonged periods of rainfall may lead to increased ground-water recharge over a region, which causes increased ground-water levels. Increased ground-water levels may lead to increased ground-water discharge to streams or reduced surface-water discharge to the ground-water body. Irrigation return flow also may contribute to increased ground-water recharge and affect the interaction between surface water and ground water in a manner similar to increased rainfall.

Ground-water withdrawals from wells, shafts, or tunnels cause a decline in ground-water levels that may extend to nearby streams. If the stream and underlying ground-water body are separated by a zone of unsaturated rock, the ground-water withdrawals will not affect streamflow. However, where the stream and ground-water body are hydraulically connected, ground-water withdrawals may cause a reduction in ground-water discharge to streams (mainly base flow) or induce flow from the stream to the aquifer.

At low altitudes, water levels in streams and in coastal ground-water bodies may be affected by ocean tides. Thus, streams may either gain or lose water during the day depending on the relative effects of the ocean tide on streams and ground-water levels.

In some valleys, perched ground water also may interact with surface water (Stearns and Vaksvik, 1935; Takasaki and Mink, 1985). In most cases, the discharge of perched water is highly dependent on rainfall. The water may be perched on sills or tuff beds, and issue from Koolau Basalt. The water also may be perched on weathered Koolau Basalt, old alluvium, or massive lava flows of Honolulu Volcanics, and issue from coarse alluvium or permeable zones of Honolulu Volcanics (Wentworth, 1951).

Other surface-water bodies, including reservoirs, wetlands, and bogs, also can interact with ground water. The bottoms of reservoirs generally are above the ground-water table and thus, reservoirs may lose water to the underlying ground-water body (see for example Young and others, 1975). Coastal wetlands may be sustained by ground water discharge, although water from the wetland may discharge to the ground-water body during parts of the day because of tide-induced changes in relative water levels. Bogs or swamps in the wet, mountainous interior areas may form where the rocks have low permeability and ground-water levels are at the land surface.

Aquatic Biota

The Hawaiian islands are the most isolated island archipelago in the world, located nearly 2,500 miles from the nearest continent, resulting in few native stream fauna compared to continental streams. Wide-spread diverse orders of insects are absent from the native biota (Howarth and Polhemus, 1991), and there are only five native fish, two native shrimp, and a few native snails. Historically, the isolation of the Hawaiian archipelago prevented large-scale colonization due to the limited dispersal mechanisms of freshwater aquatic species across the vast ocean. Most native stream species were probably derived from marine ancestors, although a few insects arrived by flight (including the ancestors of the native damselflies) or various other mechanisms (such as with the jet stream and attachment to migratory birds). This isolation enabled the few successful colonizers to undergo natural selection and adaptive radiation resulting in a high degree of endemism and specialization among the islands' biota.

The native Hawaiian freshwater fish fauna consists of three endemic gobies, *Lentipes concolor* (oopu alamoo), *Sicyopterus stimpsoni* (oopu nopili), and *Stenogobius hawaiiensis* (oopu naniha); an indigenous goby, *Awaous guamensis* (oopu nakea); and an endemic eleotrid, *Eleotris sandwicensis* (oopu akupa). The native stream fauna are well adapted to the flashy nature of Hawaiian streams and the steep topography of the watersheds. For example, all of the gobies have fused pelvic fins, allowing them to cling to the substrate and to climb steep waterfalls, although some gobies may be more capable than others of climbing high waterfalls.

Native crustaceans found in Hawaiian streams include the mountain shrimp *Atyoida bisulcata* (opae kalaole) and an estuarine species *Macrobrachium grandimanus* (opae oehaa). Also present throughout the state is the introduced Tahitian prawn (*Macrobrachium lar*), which was first released in Hawaii in 1956, and subsequently spread to nearly every stream. Native gastropods found in Hawaiian streams include the limpet-like *Neritina granosa* (hihiwai) and the estuarine *Theodoxus vespertinus* (hapawai). Snails in the families Thiaridae and Lymnaeidae also are present in some streams, more frequently along stream banks and near seeps.

Native stream fishes (gobies) and the larger crustaceans and mollusks in Hawaii are of marine origin and have retained an oceanic larval lifestage. In this type of diadromy, called amphidromy, adult lives are spent in streams, and larval periods as marine or estuarine zooplankton (Ford and Kinzie, 1982; Kinzie, 1988; McDowall, 1988). Such communities appear to be structured by the differing upstream colonization abilities of the various species (Lyons and Schneider, 1990), as well as the unpredictable patterns of larvae return to streams (Kinzie, 1988). A critical feature of the amphidromous life cycle is the need for unimpeded access to and from the ocean for downstream dispersal of larvae and upstream migration of post-larvae (Benstead and others, 1999; Brasher, 1996, McDowall, 1995; Resh and others, 1992).

Amphidromous species spawn in the stream and, with the possible exception of the goby *Awaous guamensis* (Ego, 1956; Ha and Kinzie, 1996; Kinzie, 1990), there is little evidence that the adults make a downstream migration to spawn. When the newly hatched larvae drift downstream, they remain in the water column by swimming upward and passively sinking back down as they are carried toward the sea (Bell and Brown, 1995; Lindstrom, 1998). Larvae spend from 1 to 5 months as oceanic plankton before returning to freshwater (Radtke and Kinzie, 1987; Radtke and others, 1988; Benstead and others, 1999). Studies on some of the Hawaiian amphidromous gobies indicate that adult populations are genetically undifferentiated throughout their range, larvae that return to streams are from a well-mixed population, and larvae do not return to their natal streams (Fitzsimons and others, 1990).

Of the five native amphidromous fishes, only the two species most tolerant of large variations in environmental conditions, *E. sandwicensis* and *S. hawaiiensis* (Hathaway, 1978), are found in substantial numbers in some Oahu streams (Hawaii Cooperative Park Service Unit, 1990; Kinzie, 1990). The native fishes least tolerant to habitat degradation, *L. concolor* and *S. stimpsoni* (Hathaway, 1978; Kinzie, 1990), rarely are found on Oahu (Timbol and others, 1980; Fitzsimons and others, 1990; Higashi and Yamamoto, 1993). The two native (*M. grandimanus* and *A. bisulcata*) and one introduced (*M. lar*) amphidromous shrimp are relatively common (Timbol and Maciolek, 1978).

Whereas native species are relatively uncommon in Oahu streams, introduced species are abundant. At least one introduced species has been found in all streams surveyed in Hawaii (Hawaii Cooperative Park Service Unit, 1991; Timbol and Maciolek, 1978) and the number of introduced species in Hawaiian streams is already much larger than the number of native species (Devick, 1991). Introductions of aquatic organisms into Hawaiian streams occurred in essentially four periods (as documented in Brown and others, 1999; Eldredge, 1992; Devick, 1991; Maciolek, 1984; Randall, 1978; Brock, 1960). Prior to 1900, immigrant Asian workers introduced a number of species, primarily for food. Between 1900 and World War II, mosquito control and recreation were the primary focus of introduction. From 1946 to 1961 numerous species were introduced for the control of aquatic plants, aquaculture, as baitfish, and for recreational fishing. Most recently, introductions primarily have come from the release of pets by home aquarists.

Stream alterations on Oahu, including channelization and removal of riparian vegetation, have created habitats far more suitable for introduced species than for the native species (Brown and others, 1999; Maciolek, 1977). The native species also require sufficient streamflow to provide clean, cool, freshwater (Timbol and Maciolek, 1978) and are unable to maintain populations under degraded conditions (Brown and others, 1999). But introduced species, which have broader environmental tolerances, are able to flourish in these altered stream systems (Norton and others, 1978). Furthermore, the direct effects of the introduced species on the native species are unknown, but may be extensive. Predation on the post-larvae of native species may be substantial as they attempt to migrate through altered habitat (Maciolek, 1984). In addition to whatever competition and predation introduced species directly exert on native fishes in altered streams, introduced species are a source of a number of helminth parasites (nematodes, tapeworms, and leeches) previously unknown in Hawaii (Font and Tate, 1994).

LAND USE

During the 20th century, land-use patterns on Oahu reflected increases in population and decreases in large-scale agricultural operations over time. The resident population on Oahu increased from 58,504 in 1900 to 876,156 in 2000 (fig. 16) (State of Hawaii, 2000b). In 2000, about 72 percent of the State's population resided on Oahu, and more than 40 percent of the residents on Oahu were in the Honolulu District. In recent years, the population in the Ewa District (fig. 17) has increased significantly as large-scale agricultural operations in this area have been replaced by urban developments. Between 1980 and 2000, the resident population in the Ewa District of south-central and southwestern Oahu increased 43 percent, from 191,051 to 272,328. For comparison, between 1980 and 2000, the population in the Honolulu District increased only 2 percent, from 365,048 to 372,279 (State of Hawaii, 2000b).

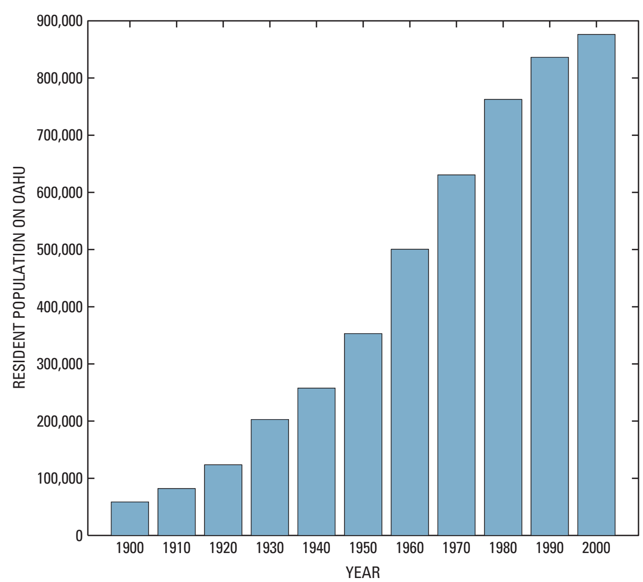


Figure 16. Resident population between 1900 and 2000, island of Oahu, Hawaii (State of Hawaii, 2000b).

Between 1946 and 1962, about 11,600 acres were converted to urban land uses (Vargha, 1962). Toward the latter part of the 20th century, the general trend of land use on Oahu has shifted from large-scale plantation agriculture to urban land use and diversified agriculture. The last two remaining sugarcane plantations on Oahu closed in the mid-1990's, and land that was once used for sugarcane commonly is used for diversified agriculture or developed for urban use. Although two large pineapple plantations continue to operate in central Oahu, some of the land previously used for pineapple cultivation has been developed for urban uses.

Zoned Land Districts

Lands in the state are classified as either agricultural, conservation, rural, or urban districts (Hawaii Revised Statutes, Chapter 205). The distribution of agricultural, conservation, and urban districts on Oahu is shown in figure 17. During 2000, no lands on Oahu were classified as rural.

Agricultural districts include "activities or uses as characterized by the cultivation of crops, orchards, forage, and forestry; farming activities or uses related to animal husbandry, aquaculture, and game and fish propagation; aquaculture, which means the production of aquatic plant and animal life for food and fiber within ponds and other bodies of water; wind generated energy production for public, private, and commercial use; bona fide agricultural services and uses which support the agricultural activities of the fee or leasehold owner of the property and accessory to any of the above activities, whether or not conducted on the same premises as the agricultural activities to which they are accessory, including but not limited to farm dwellings…, employee housing, farm buildings, mills, storage facilities, processing facilities, vehicle and equipment storage areas, and roadside stands for the sale of products grown on the premises; wind machines and wind farms; small-scale meteorological, air quality, noise, and other scientific and environmental data collection and monitoring facilities occupying less than one-half acre of land, provided that such facilities shall not be used as or equipped for use as living quarters or dwellings; agricultural parks; and open area recreational facilities, including golf courses and golf driving ranges…" (Hawaii Revised Statutes, Chapter 205-2).

Conservation districts "include areas necessary for protecting watersheds and water sources; preserving scenic and historic areas; providing park lands, wilderness, and beach reserves; conserving indigenous or endemic plants, fish, and wildlife, including those which are threatened or endangered; preventing floods and soil erosion; forestry; open space areas whose existing openness, natural condition, or present state of use, if retained, would enhance the present or potential value of abutting or surrounding communities, or would maintain or enhance the conservation of natural or scenic resources; areas of value for recreational purposes; other related activities; and other permitted uses not detrimental to a multiple use conservation concept" (Hawaii Revised Statutes, Chapter 205-2). The State manages all conservation-district lands to conserve, protect, and preserve important natural resources. Lands in the conservation districts are classified into one of five subzones (protective, limited, resource, general, or special), and land use within each subzone is restricted. The objective of each subzone is as follows: (1) (protective) to protect resources in restricted watersheds, marine, plant, and wildlife sanctuaries, and areas with significant historic, archaeological, geological, volcanological, and other unique features; (2) (limited) to limit uses where natural conditions (floods, erosion, landslides, tsunamis) may constrain human activities; (3) (resource) to properly develop areas to ensure sustained use of the natural resources of those areas; (4) (general) to designate open space where urban use may not yet be appropriate; and (5) (special) to provide for areas with unique developmental qualities that complement the natural resources of the area (Hawaii Administrative Rules, Title 13). Most of the conservation-district lands in the protective subzone on Oahu are in the mountainous interior parts of the island where ground-water recharge from infiltration of rainfall is high. Much of the lands in the resource subzone are adjacent to the lands in the protective subzone.

Although no lands on Oahu were classified as rural during 2000, a description of rural districts follows. Rural districts include activities or uses as characterized by low density residential lots, generally with no more than one dwelling house per one-half acre, in areas where city-like concentration of people, structures, streets, and urban level of services are absent, and where small farms are intermixed with low density residential lots. Urban districts include activities or uses as provided by ordinances or regulations of the county.

As of 2000, about 34 percent of the land on Oahu was classified as agricultural-district land, 40 percent was conservation, and 26 percent was urban (fig. 17) State of Hawaii, 2000b). The main urban districts are in Honolulu, the southern and central parts of central Oahu, and the southern part of windward Oahu.

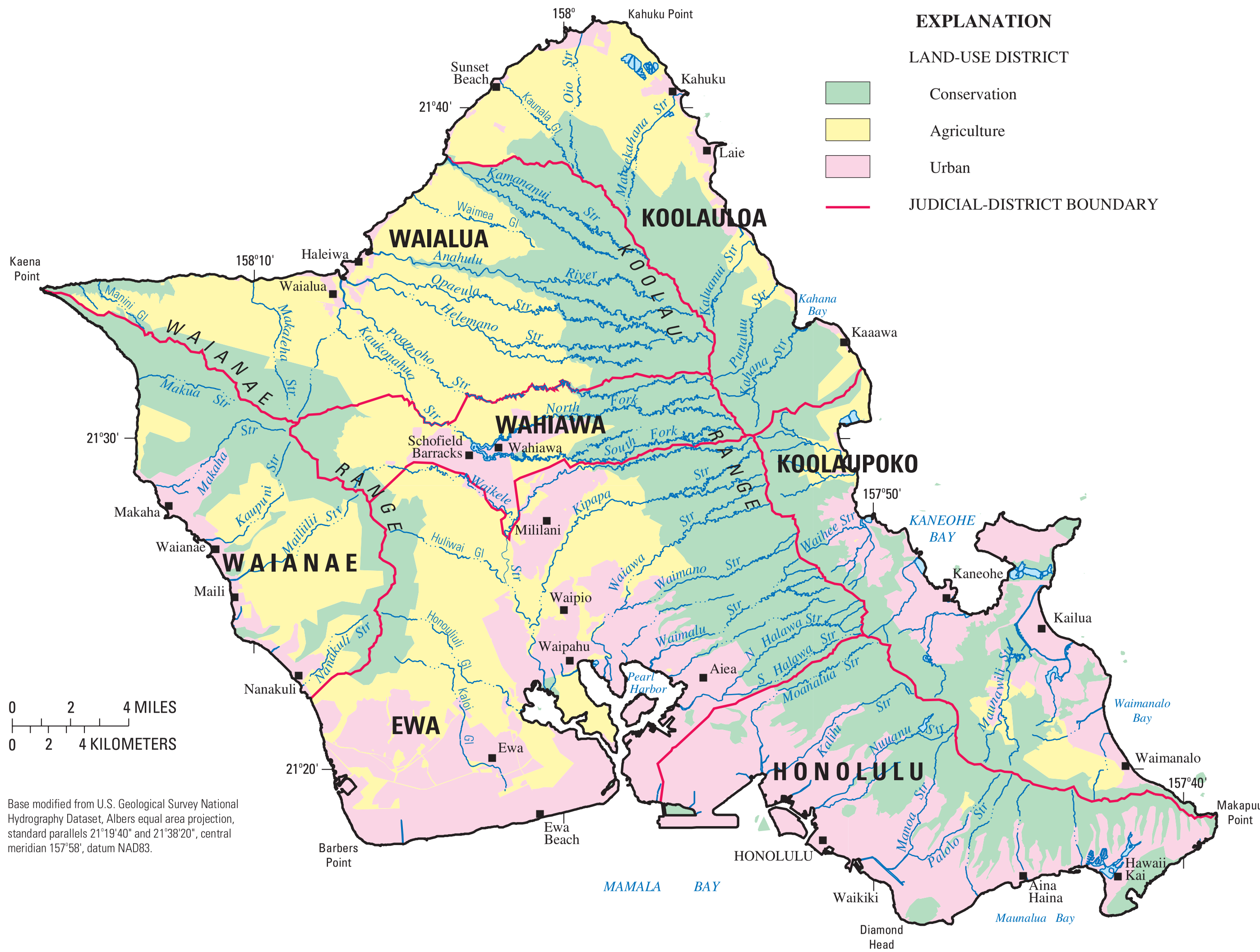


Figure 17. Land-use districts for 2000 and judicial-district boundaries (State of Hawaii, 2002a), island of Oahu, Hawaii.

Most of the agricultural districts are in the southern and northern parts of central Oahu, the northern parts of windward Oahu, and parts of the Waianae area. The conservation districts mainly are in the mountainous interior areas of the island, although some coastal areas also are designated as conservation districts.

Mapped Land Use

Districts define the type of activities that may exist in an area, although district designations do not always correspond to actual land use. For example, some areas classified as agricultural districts may be unmanaged vegetation not used for agricultural purposes. Furthermore, land-district definitions may differ from actual land-use classes in an area, depending on the land-use classification system used. For example, golf courses are considered as agricultural districts in the State system (Hawaii Revised Statutes, Chapter 205-2), whereas other classification systems consider golf courses as nonagricultural, developed land (Klasner and Mikami, in press).

A number of reports and maps were created to describe land-use conditions on Oahu during the 20th century (see for example Territorial Planning Board, 1939; Coulter, 1940; Harland Bartholomew and Associates, 1957; Land Study Bureau, 1959; Baker, 1961; Vargha, 1962; Nelson, 1963; Ching and Sahara, 1969; Sahara and others, 1972). More recently, the USGS used the Geographic Information and Analysis System (GIRAS) protocol (Mitchell and others, 1977) for collecting land-use and land-cover data on Oahu and throughout Hawaii (U.S. Geological Survey, 1979; U.S. Geological Survey, 1980). Land use and land cover were classified using the system established by Anderson and others (1976). The GIRAS data (excluding bays and estuaries) indicated that 1976–78 land use on Oahu was about 19.2 percent agricultural, 22.9 percent developed (nonagricultural), 0.04 percent barren-mining, and 57.9 percent other (including 19.4 percent rangeland, 37.7 percent forest, 0.15 percent water reservoirs, 0.39 percent wetland, and 0.26 percent barren, transitional areas) (fig. 18).

Klasner and Mikami (in press) mapped 1998 land use on Oahu using digital orthophotographs and estimated that land use was 15.4 percent agricultural, 25.7 percent developed (nonagricultural), 0.4 percent barren-mining, and 58.5 percent other (including conservation, forest reserve, natural areas, wetlands, water, barren [sand, rock, or soil] regions, and unmanaged vegetation) (fig. 18). The estimated percentage of developed (nonagricultural) land on Oahu (25.7 percent) from Klasner and Mikami (in press) corresponds closely to the percentage of land (26 percent) classified as urban districts in 2000 (State of Hawaii, 2000b), and represents an increase in developed (nonagricultural) areas relative to the 1976–78 GIRAS data. The estimated percentage of agricultural land (15.4 percent) from Klasner and Mikami (in press) is considerably less than the percentage of land (34 percent) classified as agricultural districts on Oahu in 2000 (State of Hawaii, 2000b), which reflects differences between district designations and actual land use as well as differences in classification systems. Agricultural land on Oahu decreased between 1976–78 (19.2 percent) (U.S. Geological Survey, 1979; 1980) and 1998 (15.4 percent) (Klasner and Mikami, in press).

Agriculture

Prior to the introduction of large-scale sugarcane and pineapple cultivation on Oahu, taro was one of the main crops grown on Oahu. Although sugarcane and pineapple row crops dominated the landscape on Oahu during the 20th century, many other crops also were cultivated. Pineapples continue to be cultivated in central Oahu, but sugarcane is no longer cultivated on Oahu (as of 1996). A number of orchards (including banana, coffee, guava, macadamia nut, papaya, and coconut) and row crops other than sugarcane or pineapples (including corn, fruits, vegetables, and wetland crops) were planted on Oahu in 1998 (Klasner and Mikami, in press).

In 1998, a total of 59,415 acres (33,274 acres planted or cultivated, 771 acres used for livestock, 193 acres used for aquaculture, 3,800 acres of small-scale rural areas, and 21,377 acres of abandoned land) was classified as agricultural land (Klasner and Mikami, in press). The planted or cultivated areas included orchards, row crops, horticulture, shade houses, and grasses used for pasture, grazing, and biomass. The abandoned agricultural areas (commonly former sugarcane or pineapple fields) included areas where evidence of past agriculture was evident.

Sugarcane

Prior to 1880, lack of irrigation water in the drier parts of Oahu generally limited the cultivation of

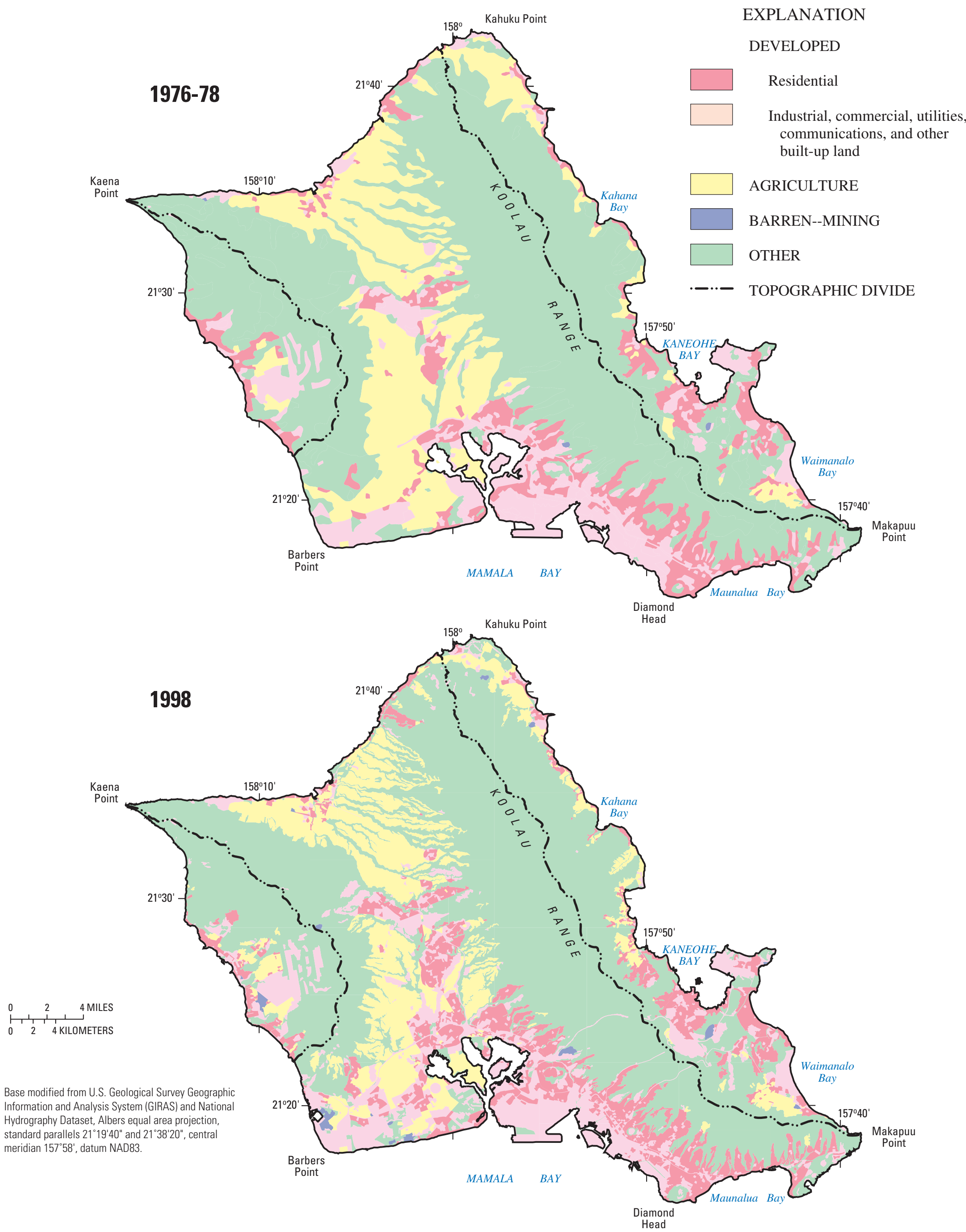


Figure 18. Land use and land cover for 1976–78 and 1998 conditions, island of Oahu, Hawaii (modified from U.S. Geological Survey, 1979; 1980, and Klasner and Mikami, in press).

sugarcane to areas with sufficient rainfall and surface water to meet crop water requirements. In 1880, 2,635 acres of sugarcane were planted on nine plantations on Oahu, and most of these plantations were on the wet, windward side of the island (Stearns and Vaksvik, 1935). The Waianae plantation was located in the dry western part of the island and used water developed by tunnels in the Waianae Range. The 1879 discovery of artesian ground water in the dry, southern coastal plain of Oahu paved the way for expansion of sugarcane cultivation on the island. By 1930, more than 350 wells had been drilled by sugarcane plantations, mainly for irrigation water (Stearns and Vaksvik, 1935), and 43,158 acres of sugarcane were planted on 8 plantations (Doty, 1931).

In 1940, the seven remaining sugarcane plantations on Oahu (Ewa, Honolulu, Kahuku, Oahu, Waialua, Waianae, and Waimanalo plantations) planted a combined total of 42,798 acres of sugarcane (Hawaii Sugar Planters' Association, 1941). The Waianae, Waimanalo, and Honolulu plantations were shut down in 1947. A resort and two golf courses occupy much of the former plantation lands in Waianae (Dorrance and Morgan, 2001). A U.S. Air Force station, rural lots, and field crops occupy much of the former plantation lands in Waimanalo. Prior to 1947, a significant part of the Honolulu plantation was given up for military use near Pearl Harbor. In 1947, the remaining lands of the Honolulu plantation were acquired by the Oahu Sugar Co., which was one of the four remaining plantations on the island.

Dale (1967) documented the changes in sugarcane acreage during 1931–65 in the Pearl Harbor area of southern Oahu: between 1939 and 1944, about 3,000 acres on the coastal plain were converted to military use; between 1950 and 1955, about 2,000 acres were converted to unirrigated pineapple fields; between 1960 and 1962, about 2,000 acres were converted from unimproved land to sugarcane; and between 1949 and 1964, about 2,000 acres were converted to urban use.

In 1970, the Ewa plantation was sold to the Oahu Sugar Co., and, in 1971, the Kahuku plantation was shut down. Former plantation lands in Kahuku are now used for housing, grazing, field crops, and orchards. In 1980, the two remaining sugarcane plantations, Oahu Sugar Co. in southern Oahu and Waialua Sugar Co. in northern Oahu, planted a combined total of 33,100 acres, and by 1990 the combined total was 23,600 acres (Hawaii Agricultural Reporting Service, 1981; 1991). The reduction in sugarcane acreage between 1980 and 1990 mainly reflected increased urbanization in southern Oahu. Oahu Sugar Co. shut down after the 1995 harvest (April 1995), and Waialua Sugar Co. shut down after the 1996 harvest (October 1996). In southern Oahu, much of the former sugarcane lands of the Oahu Sugar Co. is currently (2003) urbanized or used for diversified agriculture. In northern Oahu, much of the former sugarcane lands of the Waialua Sugar Co. is used for diversified agriculture. Areas used for sugarcane cultivation during part or all of the period between about 1950 and 1996 are shown in figure 19.

On Oahu, most irrigated sugarcane was grown at altitudes of about 10 to 900 ft. However, unirrigated sugarcane was cultivated at altitudes up to about 1,250 ft. Sugarcane cultivation practices varied among the plantations and were dependent on the variety of sugarcane as well as local field conditions. Sugarcane was grown year-round on Oahu, and generally was harvested on a 2-yr crop cycle. A crop was initiated with the planting of sugarcane seeding stalks. One or two ratoon crops generally followed the initial crop. Prior to the 1970's, the main method of irrigation on Oahu was the furrow method, in which water was delivered to the fields through a system of ditches and in-field furrows. Fields generally were irrigated with the furrow method between 20 and 40 times over the 2-yr crop cycle, with each application requiring from 4 to 10 in. of water (Yim and Dugan, 1975). Dale (1967) estimated that an average of about 112 in/yr of irrigation water was applied with the furrow method in southern Oahu between 1931 and 1965. Estimates of the irrigation efficiency (ratio of water volume used by the crop to water volume applied) for the furrow method range from about 0.3 to 0.7 (Dale, 1967; Fukunaga, 1978; Giambelluca, 1983; Mink, 1980).

Although overhead sprinkler systems were introduced on Oahu during the 1960's to improve irrigation efficiency (Hall, 1965), the drip-irrigation method began replacing the furrow method during the 1970's (Gibson, 1979). Estimates of the irrigation efficiency with the drip method range from about 80 to 95 percent (Fukunaga, 1978). The drip method uses lateral tubes with small emitters that are spaced to deliver water to the plants and maintain adequate soil moisture in the plant root zone. With the drip method, water was applied daily during peak-use periods at a rate of about

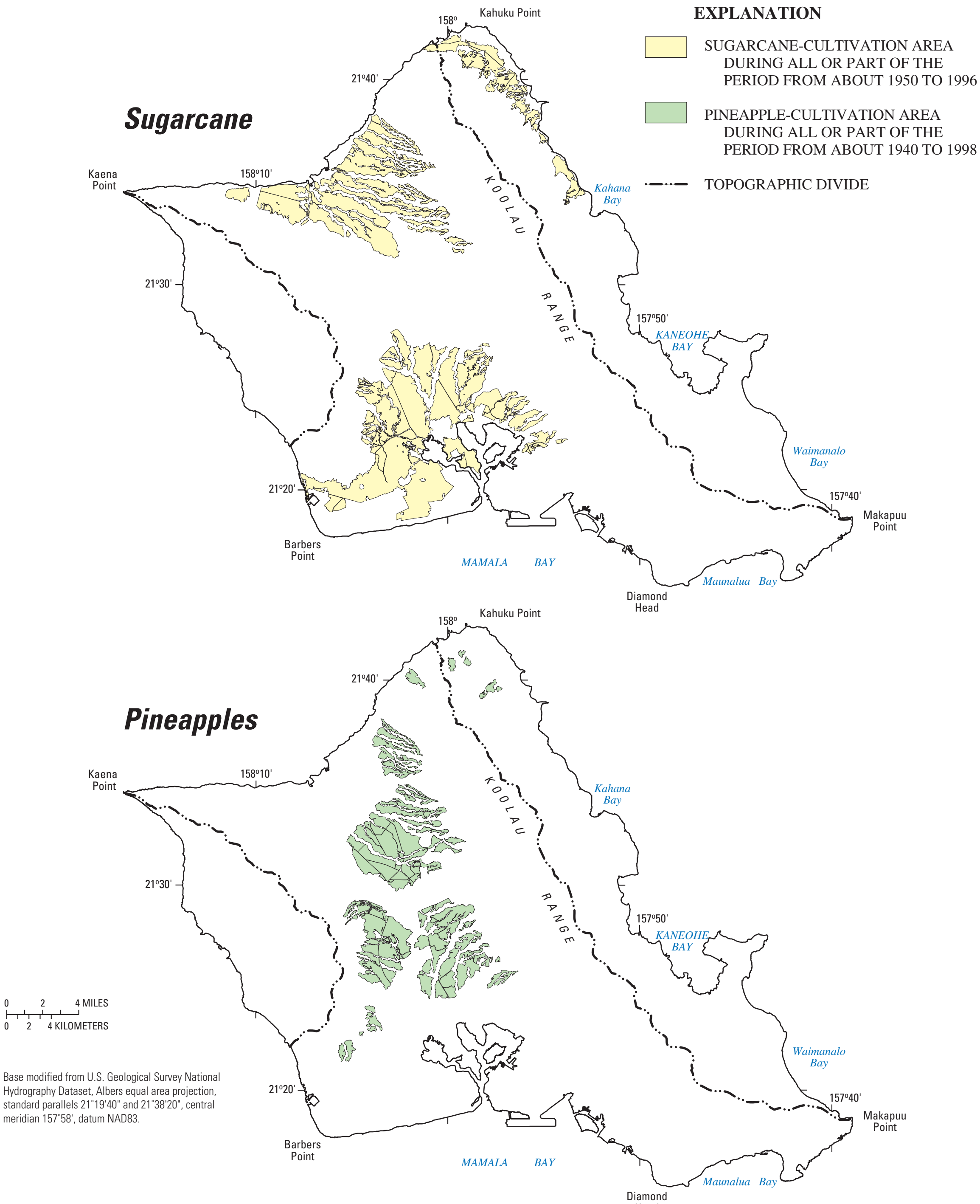


Figure 19. Areas used for sugarcane and pineapple cultivation, island of Oahu, Hawaii.

0.03 in/hr over a 12-hour period (Yamauchi and Bui, 1990). Irrigation water generally was discontinued 2 to 3 months before harvest to enhance sugar storage (Yim and Dugan, 1975).

Fertilizers for sugarcane crops were applied in solid or liquid forms by mechanical or aerial broadcasting, or in irrigation water (Yim and Dugan, 1975). About 250 to 400 lb/acre of nitrogen, 0 to 350 lb/acre of K_2O, and 0 to 500 lb/acre of P_2O_5 were applied to each crop, the quantities depending on soil, climate, and management factors (Green and Young, 1970). The nitrogen and potassium fertilizers generally were applied during the first 9 months of crop growth, and the phosphorus was applied at the time of planting (Yim and Dugan, 1975). Phosphate fertilizers may contain large amounts of cadmium and zinc as impurities (McMurtry and others, 1995).

Although published information on pesticide use by sugarcane growers on Oahu is not available, statewide summaries of pesticide use by sugarcane growers are available for 1964 through 1968 (State of Hawaii, 1969), 1973 (Pacific Biomedical Research Center, 1975), 1977 (Takahashi, 1982), and 1982 through 1991 (R.R. Roberts and S.A. Whalen, Hawaii Sugar Planters' Association, unpub. data, 1992). On the basis of these statewide summaries, herbicides were the main form of pesticides used for sugarcane cultivation in Hawaii. Herbicides generally were applied during the first several months of the 2-yr crop cycle, prior to when the crop canopy covered the soil (Pacific Biomedical Research Center, 1975; R.R. Roberts and S.A. Whalen, Hawaii Sugar Planters' Association, unpub. data, 1992). The herbicides used in greatest quantities by sugarcane growers in Hawaii included ametryn, atrazine, dalapon, diuron, and 2,4-D. During the 1960's, trichloroacetic acid (TCA) and pentachlorophenol also were extensively used, although the pentachlorophenol registration was cancelled in 1971 (State of Hawaii, 1969; Pacific Biomedical Research Center, 1975). During the 1980's and early 1990's, glyphosate and hexazinone were used in significant quantities, and trifluralin use increased between 1987 and 1991 (R.R. Roberts and S.A. Whalen, Hawaii Sugar Planters' Association, unpub. data, 1992). In addition to herbicides, sugarcane growers used fungicides, growth regulators, insecticides, and rodenticides (table 4 at end of report). (Because specific information on pesticide use by sugarcane growers on Oahu was not available, it is possible that some of the pesticides listed in table 4 may not have been used on Oahu. Furthermore, additional pesticides not listed in table 4 may have been used on Oahu, particularly during periods for which no information on pesticide use was available.)

Pineapples

In 1885, a horticulturist named Captain John Kidwell made the first commercial planting of pineapples on 4 or 5 acres in Manoa Stream valley in Honolulu (Cooke, 1949; Elder, 1968). Although pineapples also were cultivated in windward Oahu during the 1900's (Elder, 1968), most of the pineapple cultivation on the island during the 20th century was in central Oahu on three plantations. James Dole formed the Hawaiian Pineapple Co. in 1901, which later became the Dole Food Co., Inc. that continues to grow pineapples in central Oahu in 2003. Libby, McNeill, and Libby began operation on Oahu in 1909, when they purchased land used for pineapple cultivation in windward Oahu, and cultivated pineapples in central Oahu until the early 1960's. Del Monte Corp. began operations on Oahu in 1917 as a division of California Packing Corp. (Pineapple Growers Association of Hawaii, 1969), and continues to grow pineapples in central Oahu in 2003.

In 1900, a total of about 600 acres of land was used for pineapple cultivation on Oahu (Vaksvik, 1939). By 1920, the land area on Oahu used for pineapple cultivation increased to 27,700 acres, and in 1937 the total decreased to 15,000 acres as former pineapple fields apparently were used for other purposes (Vaksvik, 1939).

Pineapples require much less water than sugarcane, and can be grown in areas of low to moderate rainfall with limited or no irrigation. Irrigation is applied using overhead sprinklers during periods of low rainfall or through drip-irrigation lines at the rate of about 0.25 in. per week (State of Hawaii, 1983). Most pineapples on Oahu have been cultivated in central Oahu at higher altitudes than areas of sugarcane cultivation. Areas used for pineapple cultivation during part or all of the period between about 1940 and 1998 are shown in figure 19.

Pineapples are grown year-round on Oahu, and fields are replanted every three to five years. The initial crop, which is harvested about 18 months after planting, is followed by one or two ratoon crops before the land is prepared for the next planting. Following the harvest of the final ratoon crop, existing pineapple plants are knocked down with machinery (discs or stump cutters), and the plant material is left on the surface and may subsequently be burned. Fields generally are plowed and disced several times prior to planting. Planting material commonly consists of crowns (vegetative shoot at the top of the fruit), although slips (small shoots on the peduncle below the fruit) and suckers (shoots from some of the leaf axils on the main stem) also are used (Collins, 1964). Before planting, the soil is fumigated and a polyethylene mulch paper, typically 32-in. wide, is placed over the prepared soil in rows that mark the planting beds. Before introduction of the polyethylene mulch paper, a heavy (0.016-in thick), tar-impregnated paper was used (Cooke, 1949). The mulch paper is used to (1) maintain warm soil temperatures that enhance early plant growth, (2) suppress weed growth, (3) preserve soil moisture, (4) reduce leaching of nutrients and loss of volatile fumigants (Collins, 1964). Soil fumigants are injected into the soil at a depth of about 8 to 10 in. to control nematodes that attack the roots of pineapple plants. Planting generally occurs 48 hours or more after fumigation (State of Hawaii, 1983).

A total of about 200 to 300 lb/acre of nitrogen is used for each crop cycle, with 50 to 100 lb/acre applied as ammonium sulfate as the mulch paper is laid down. Subsequent nitrogen applications are in the form of post-plant sprays of urea at rates of 5 to 20 lb/acre (Yim and Dugan, 1975). Phosphorus, potassium, and magnesium also are used where necessary in much smaller amounts (Yim and Dugan, 1975).

Statewide summaries of pesticide use by pineapple growers are available for 1964 through 1968 (State of Hawaii, 1969), 1969 through 1973 (Pacific Biomedical Research Center, 1975), 1977 (Takahashi, 1982), and 1983 (D. Yoshizu, Hawaii State Department of Agriculture, unpub. data, 1987). However, information on pesticide use for pineapple cultivation on Oahu is only available for 1969 through 1973 (Pacific Biomedical Research Center, 1975). Fumigants are the pesticides used in greatest quantities by pineapple growers. Prior to the 1942 introduction of DD (a mixture of 1,3-dichloropropene and 1,2-dichloropropane), chloropicrin was sometimes used for soil fumigation by pineapple growers in Hawaii (Carter, 1945; Cooke, 1949). Dole Co. selected DD as its primary soil fumigant in 1948, and in 1959 began using DBCP (1,2-dibromo-3-chloropropane) in conjunction with DD on Oahu until 1977 when it phased out the use of DBCP. Dole Co. used EDB (1,2-dibromoethane) on a limited basis between 1948 and 1955 (primarily for post-plant applications) and began significant use of EDB on Oahu between 1978 and 1984 (Oki and Giambelluca, 1987). Del Monte Corp. selected EDB as its primary soil fumigant in 1948, and continued to use EDB until 1983. Del Monte Corp. did not use DBCP on Oahu except on an experimental basis (State of Hawaii, 1983). The remaining pineapple plantation on Oahu, Libby, probably used DD on its fields (Oki and Giambelluca, 1987). The fumigants telone II (1,3-dichloropropene) and methyl bromide (bromomethane) have been most commonly used in Hawaii in recent years (Sipes, 2000), although the U.S. Environmental Protection Agency (USEPA) is currently requiring the phase out of methyl bromide production because of its effects on ozone in the atmosphere (U.S. Environmental Protection Agency, 2002b). In addition to soil fumigants, pineapple growers on Oahu have used fungicides, herbicides, insecticides, growth regulators, and nematicides (table 4).

Other Row Crops and Orchards (Diversified Agriculture)

In 1900, rice, bananas, vegetables, sisal, and other field crops were grown on Oahu in addition to sugarcane and pineapples (Vaksvik, 1939). By 1937, sisal was no longer cultivated, but avocados (540 acres), bananas (995 acres), macadamia nuts (72 acres), papayas (300 acres), vegetables (1,550 acres), wetland crops such as rice and taro (1,275 acres), other fruits (128 acres), and unspecified field crops (260 acres) were cultivated on a total of 5,120 acres mainly at altitudes below 1,000 ft (Vaksvik, 1939). In 1998, orchards and row crops other than pineapples were grown on 11,690 acres (Klasner and Mikami, in press) following the closure of the remaining sugarcane plantations, which made land available for other agricultural uses. During 1998, bananas (1,183 acres), coconuts (118 acres), coffee (352 acres), guavas (13 acres), macadamia nuts (33 acres), papayas (1,160 acres), corn (835 acres), fruits and vegetables (6,830 acres), wetland crops (305 acres), and other orchard and row crops (861 acres) were grown mainly in central and windward Oahu (Klasner and Mikami, in press).

Between 1950 and 2000, various fruits, vegetables, and other crops were grown on Oahu (table 5), and a variety of pesticides, including fungicides, herbicides, insecticides, and fumigants, were used (table 4).

Table 5. Selected diversified crops grown during 1950–2000, island of Oahu, Hawaii

[nd, no data for Oahu, although statewide total may exist; <, less than; negl., negligible; sources are Hawaii Agricultural Extension Service (1951), Hawaii Cooperative Extension Service (1961), Hawaii Crop and Livestock Reporting Service (1971), Hawaii Agricultural Reporting Service (1981), Hawaii Agricultural Reporting Service (1991), and Hawaii Agricultural Statistics Service (2001)]

Crop	Number of acres					
	1950	1960	1970	1980	1990	2000
Fruits						
avocados	6	5	nd	nd	nd	nd
bananas	872	747	415	470	505	760
guavas	nd	nd	nd	<480[a]	<655[a]	<460[d]
mangos	27	0	nd	nd	nd	nd
papayas	680	235	45	75	40	510
Vegetables and melons						
beans, snap	191	87	75	25	10	65
beets	6	nd	nd	nd	nd	nd
broccoli	30	25	8	nd	nd	nd
cabbage, head	46	16	3	<100[b]	<190[b]	<350[b]
cabbage, other	214	122	115	nd	<110[d]	<95[d]
cantaloupes	nd	5	nd	nd	nd	nd
carrots	12	nd	nd	nd	nd	nd
celery	2	nd	0	0	0	0
corn	169	260	300	195	105	285
cucumbers	146	89	55	80	70	200
daikon	51	70	70	<90[c]	<115[c]	<100[d]
dasheens	7	nd	0	nd	nd	nd
eggplant	30	20	15	29	20	40
ginger root	nd	15	4	nd	nd	nd
lettuce	59	110	120	120	<50[f]	<190[b]
lotus root	50	66	50	35	nd	nd
onions, dry	nd	25	nd	<5[b]	<5[b]	<150[b]
onions, green	33	50	70	75	150	125
peppers, sweet or green	35	36	20	5	<5[f]	nd
potatoes	21	nd	nd	negl.	nd	nd
pumpkins	5	2	5	nd	nd	nd
squash	15	nd	4	nd	nd	<115[b]
sweet potatoes	135	77	35	45	5	<195[b]
tomatoes	223	66	15	10	5	nd
watercress	24	30	28	nd	nd	nd
watermelons	625	248	160	65	15	555
yam bean root	4	nd	nd	nd	nd	nd
Other crops						
coffee	nd	nd	nd	0	nd	<4,600[d]
macadamia nuts	180	135	nd	<1,190[d]	nd	nd
taro	426	115	20	<80[e]	<85[e]	<100[c]

[a]Combined acreage from Oahu, Maui, Molokai, and Kauai
[b]Combined acreage from Oahu, Kauai, and Hawaii
[c]Combined acreage from Oahu and Maui
[d]Combined acreage from Oahu, Kauai, and Maui
[e]Combined acreage from Oahu, Maui, and Molokai
[f]Combined acreage from Oahu and Kauai

Horticulture and Shade Houses

Common horticultural crops and plants grown on Oahu include flowers, potted plants, ornamental plants, turf grass, and ti plants. Some of the plants are grown in shade houses. In 1980, 374 acres were used for floriculture and nursery products on Oahu (Hawaii Agricultural Reporting Service, 1981), and in 1990, 230 acres were used for the same purpose (Hawaii Agricultural Reporting Service, 1991). By 2000, land previously used for sugarcane cultivation became available and the total acreage used for floriculture and nursery products on Oahu increased to 579 acres (Hawaii Agricultural Statistics Service, 2001). A variety of pesticides have been used in nurseries and for ornamental plants (table 4) (State of Hawaii, 1969; Takahashi, 1982; State of Hawaii, 1986).

Livestock Operations

Livestock operations associated with beef and dairy cattle, hogs and pigs, and poultry exist in the windward, central, and Waianae areas of Oahu (Klasner and Mikami, in press; Hawaii Agricultural Statistics Service, 2001). In 1950, about 546 commercial-scale livestock operations existed on Oahu, and about 30,000 acres of land was used for pasture and grazing (Hawaii Agricultural Extension Service, 1951). In 1970, about 39,000 acres of land was used for pasture and grazing (Hawaii Crop and Livestock Reporting Service, 1971). Klasner and Mikami (in press) estimated that about 7,000 acres was used for pasture and grazing in 1998, although it is uncertain whether the classification system used by Klasner and Mikami is comparable with the earlier classifications (Hawaii Agricultural Extension Service, 1951; Hawaii Crop and Livestock Reporting Service, 1971).

Only limited information on pesticide use related to livestock operations or pesticides applied on pasture and grazing land is available (table 4) (State of Hawaii, 1969; Takahashi, 1982).

Developed (Nonagricultural) Land

Developed (nonagricultural) areas on Oahu are used for residential, commercial, and industrial purposes, as well as for social services (government and education), public infrastructure (utilities, waste management, airport, automotive, and port), and open space (recreation, maintained vegetation including golf courses, and vacant). Of the 98,948 acres of developed (nonagricultural) land existing in 1998, Klasner and Mikami (in press) classified 44,816 acres as residential, 14,649 acres commercial, 3,814 acres industrial or manufacturing, 5,159 acres social services, 12,906 acres public infrastructure, and 17,604 acres open space.

Information on land ownership from 1988 indicates that the county, State, and Federal governments own about one-third of the land on Oahu (State of Hawaii, 1999b). Government-owned lands are used for a variety of purposes, including military-related activities, parks and golf courses, roads, highways, and parking lots, education, public-housing, offices, agricultural experiment stations, landfills, and conservation land. Significant areas currently or previously used for military-related activities are in the Schofield and Wahiawa areas of central Oahu, the Pearl Harbor and Barbers Point areas of southern Oahu, parts of the Waianae area of western Oahu, and the Kaneohe and Waimanalo areas of windward Oahu.

Residential Areas

Residential areas on Oahu vary in density, ranging from high-density areas in Honolulu with closely spaced multistory buildings and large paved areas, to low-density areas in western and northern Oahu with single-family, unattached homes. In high-density areas of Honolulu, Giambelluca (1983) estimated that about 15 percent of the area is covered by permeable surfaces, whereas in low-density areas, about 80 percent or more of the area may be covered by permeable surfaces.

A variety of chemical uses are common in residential areas, including chemicals related to use of pesticides, fertilizers, household cleaners, paints, solvents, oil, grease, fuels, pharmaceutical products, and caffeine. Pesticides used include insecticides, herbicides, fungicides, acaricides, mulluscicides, fungicides, rodenticides, and fumigants. Pesticides are commonly applied on lawns and gardens, inside homes, and on pets, and may be used in liquid, aerosol, bait, dust or powder, and granule formulations. Household surveys conducted in 1974 in the Hawaii Kai area of eastern Oahu (Pacific Biomedical Research Center, 1975), 1977 for unspecified areas in the state (Takahashi, 1982), and 1989 in the Waipio area of central Oahu (Oki and others, 1990) identified a variety of pesticides being used (table 4). The 1989 survey of the Waipio area (Oki and others, 1990) was limited to pesticide use on lawns and gardens. Estimated pesticide-application rates for individual households in the Waipio area varied over two orders of magnitude for the commonly used pesticide diazinon (Oki and others, 1990), and this may be indicative of pesticide- and fertilizer-application rate variability in other areas. A limited survey of seven retail outlets in central Oahu during 1989 identified pesticides that were readily available to residents in central Oahu (table 4) (Oki and others, 1990).

Commercial and Industrial Areas

A wide range of commercial and industrial activities exists in developed areas on Oahu, which has its central business district located in Honolulu. General retail stores and restaurants exist in a variety of settings, from large-scale shopping malls to small neighborhood shops and restaurants. Retail stores range from large department, electronics, office-supply, appliance, and furniture stores and supermarkets to smaller stores and shops that specialize in goods including clothing, food, books, sports- and hobby-related activities, antiques, arts and crafts, pets, and others. One of the main industries on Oahu is the tourism industry. Numerous hotels, restaurants, bars, and retail stores can be found in the Waikiki area of Honolulu, a tourist destination.

Business activities on Oahu that may involve chemical use include pest-control, wood treating, utilities, oil refining, petroleum-product distribution, gasoline stations, construction, metal plating and protective coating, automobile repair and painting, laundering and dry cleaning, photograph processing, medical and dental laboratories, recycling and waste disposal, furniture refinishing, and others. Some of the substances likely to be found in commercial and industrial areas include pesticides, wood preservatives, petroleum products, solvents and degreasing agents, dry-cleaning chemicals, paint-stripping chemicals, heavy metals, and others, although information on chemical use for most commercial and industrial activities is not available. Petroleum-based fuels, oil and lubricants, polychlorinated biphenyls (PCBs), solvents, paints and paint thinners, acids, and metals are some of the products previously or currently used in military, commercial, and industrial areas (Harding Lawson Associates, 1996; The Environmental Company, 2000; The Environmental Company, 2001).

Pest-control operators use insecticides, fumigants, fungicides, herbicides, and rodenticides, although insecticides for termite treatment are probably most common (table 4) (State of Hawaii, 1969; Takahashi, 1982; Oki and others, 1990). Use of pesticides by pest-control operators is not limited to commercial and industrial areas. Chlordane was one of the most heavily used termiticides on Oahu prior to its use being banned by the USEPA in 1988. Other chlorinated hydrocarbon insecticides used to control termites and structural pests included aldrin, dieldrin, and heptachlor (State of Hawaii, 1969). Chlorpyrifos, permethrin, cypermethrin, and isofenphos were commonly used on Oahu as replacements for chlordane (Oki and others, 1990).

Wood preservatives and insecticides are used for wood treatment on Oahu. During 1973 (Pacific Biomedical Research Center, 1975), 1977 (Takahashi, 1982) and 1983 (D. Yoshizu, Hawaii State Department of Agriculture, unpub. data, 1987) pesticides used for wood treatment on Oahu included arsenic pentoxide, arsenic acid, chromium trioxide, chromic acid, copper acetoarsenite, copper oxide, dieldrin, lindane, pentachlorophenol, and tributyl tin oxide (TBTO).

Social Services

Land used for social services includes government and private areas serving schools, universities, government administrative offices, and health and welfare facilities (hospitals, public service venues, and recreation structures including enclosed stadiums, gymnasiums, and swimming-pool complexes) (Klasner and Mikami, in press).

Herbicides and insecticides commonly are used in and around buildings and schools, oftentimes for termite control. Although limited information on historical use of pesticides by government agencies is available (table 4) (State of Hawaii, 1969; Pacific Biomedical Research Center, 1975; Takahashi, 1982), information on other chemical use is limited.

Public Infrastructure

Most of the wastewater generated in developed (nonagricultural) areas is collected in sewer systems and pumped to government or private wastewater treatment plants (table 6). Although most of the treated wastewater effluent is discharged to the ocean through outfalls (fig. 20), some of the treated wastewater is injected into disposal wells, discharged to surface-water bodies, pumped to leach fields or evaporation ponds, or reused for irrigation. The City and County of Honolulu operates eight wastewater treatment plants on Oahu: four discharge treated effluent to the ocean through outfalls, one discharges to the South Fork of Kaukonahua Stream, and the remaining three discharge to injection wells. The military also operates several wastewater treatment plants on Oahu, one of which discharges directly into an irrigation system in central Oahu.

About 50 private wastewater treatment plants are operated on Oahu. Most of the wastewater treated by private plants on Oahu is discharged to injection wells, although one plant in eastern Oahu discharges treated effluent to the ocean through an outfall. Most injection wells are located seaward of the underground-injection control (UIC) line established by the State Department of Health to protect ground-water resources (fig. 20).

Table 6. Wastewater discharges on Oahu, Hawaii (City and County of Honolulu, 2001)

[Mgal/d; million gallons per day]

Source	Discharge (Mgal/d)	Comments
Cesspools	3.8	estimated assuming 80 gallons per day per person
Septic tanks and other individual wastewater treatment systems	0.2	estimated assuming 80 gallons per day per person
Private wastewater treatment plants (excluding East Honolulu plant)	2.8	design flow
East Honolulu wastewater treatment plant	3.0	flow in 1985
City and County wastewater treatment plants		
Honouliuli	26.7	average flow during 2000
Kahuku	0.1	average flow during 2000
Kailua	12.9	average flow during 2000
Paalaa Kai	0.1	average flow during 2000
Sand Island	66.1	average flow during 2000
Wahiawa	2.0	average flow during 2000
Waianae	3.2	average flow during 2000
Waimanalo	0.6	average flow during 2000
Military wastewater treatment plants		
Fort Kamehameha	7	flow during the 1990's
Kaneohe Marine Corps Base	1.4	estimated for 2000

During 2001, more than 200 injection wells existed on Oahu.

In areas that are not connected to a sewer system, privately owned cesspools and septic tanks commonly are used. About 5 percent of the population relies on cesspools or septic tanks, and although most of the cesspools are in the windward and northern Oahu areas, cesspools also exist in the Honolulu area (fig. 20) (City and County of Honolulu, 2001). In 2000–2001, about 13,000 cesspools were used on Oahu (City and County of Honolulu, 2001), and some were located inland from the UIC line. Construction of new cesspools on Oahu is now banned.

Storm-water runoff is collected by a system that is separate from the sewer system. Storm-water runoff in developed (nonagricultural) areas commonly is collected and conveyed to streams without treatment and ultimately discharges to the ocean.

Pesticides used by utilities (gas, electric, and telephone) in Hawaii during 1977 included herbicides (2,4-D, 2,4,5-T, amitrole, bromacil, cacodylic acid, diuron, glyphosate, MSMA, pentachlorophenol, sodium chlorate, and sodium metaborate) and insecticides (bendiocarb, chlordane, chlorpyrifos, and heptachlor) (Takahashi, 1982). During 1977, the Honolulu Board of Water Supply used the herbicides AMA, atrazine, dalapon, glyphosate, and paraquat, and small amounts of the insecticide carbaryl (Takahashi, 1982). Information on pesticide use during other periods and other chemical use by utilities was not available.

Pesticides are commonly used along roads and runways by government agencies (State of Hawaii, 1969; Pacific Biomedical Research Center, 1975; Takahashi, 1982). On Oahu during 1977, the State Department of Transportation used both herbicides (atrazine, cacodylic acid, dalapon, dicamba, diuron, MSMA, paraquat, and trifluralin) and insecticides (carbaryl, chlordane, malathion, metaldehyde, and others) (Takahashi, 1982). The county government used the herbicides bromacil, dalapon, diquat, and diuron for road maintenance during 1977 (Takahashi, 1982).

Open Space

Open space includes urban parks, recreation areas and associated facilities, golf courses, playing fields, cemeteries, and other maintained, semimaintained, or vacant lots where structures occupy less than 25 percent of the area (Klasner and Mikami, in press). Various county, State, and Federal agencies commonly use herbicides and insecticides in parks, landscaped areas, botanic gardens, golf courses, cemeteries, and other

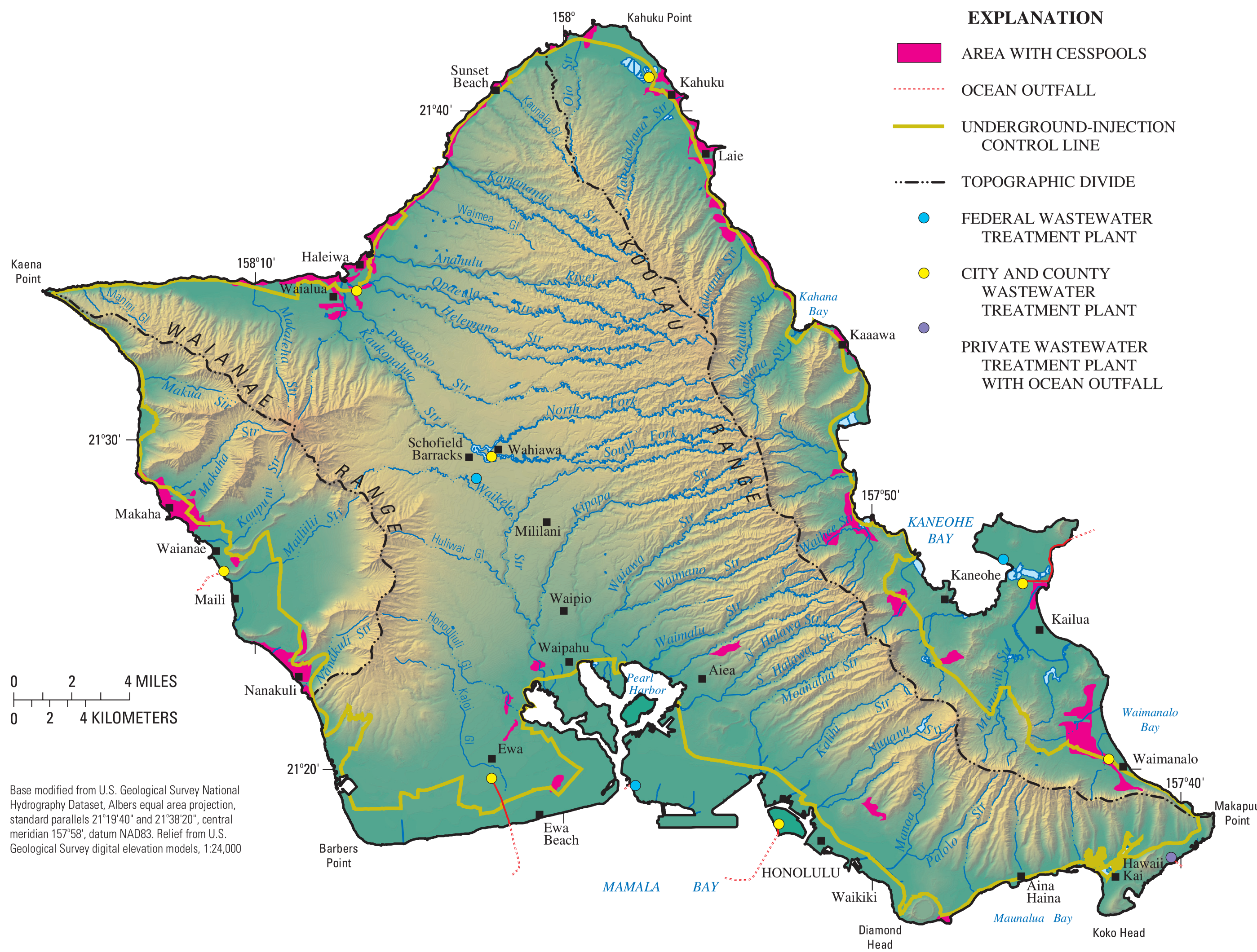


Figure 20. Ocean outfalls, selected wastewater treatment plants, areas with cesspools, and State underground-injection control (UIC) line, island of Oahu, Hawaii (modified from City and County of Honolulu, 2002; 2001, U.S. Department of the Navy, 2001, and State of Hawaii digital data).

open spaces on Oahu. Limited information on historical use of pesticides by government agencies is available (table 4) (State of Hawaii, 1969; Pacific Biomedical Research Center, 1975; Takahashi, 1982), although information may not be available to determine whether the pesticides were used only in open spaces.

The county, the military, resorts, and other private entities manage golf courses on Oahu. Pesticide-use information for golf courses is available for 1967–69 from three county golf courses on Oahu and a private golf course at an unspecified location in the State (State of Hawaii, 1969), for 1977 from county golf courses on Oahu (Takahashi, 1982), and for 1990–91 from 37 golf courses in the State (Brennan and others, 1992) (table 4). Results from the 1990–91 survey of golf-course managers in Hawaii indicated that 30 different pesticides were being used, with herbicides being the most commonly used pesticide, followed by fungicides, insecticides, and algicides (table 4) (Brennan and others, 1992). The herbicide MSMA accounted for over 67 percent of total herbicide use, and about 53 percent of total pesticide use. Resort courses were found to apply pesticides at the highest rates (14.7 lb active ingredient per acre per year), whereas county-managed golf courses and privately managed golf courses that are open to the public applied pesticides at the lowest rates (6.21 to 7.12 lb active ingredient per acre per year) (Brennan and others, 1992).

WATER USE

Water-use patterns on Oahu have reflected land-use patterns over time. Water use for agricultural purposes increased following the 1879 discovery of artesian ground water in southwestern Oahu, which led to the expansion of sugarcane cultivation to the dry areas of the island. Diverted surface water supplemented the ground-water resources used for sugarcane irrigation.

Ground Water

By early 1882, a total of 15 flowing wells and 3 nonflowing wells had been drilled on Oahu, and by about 1930, nearly 700 wells had been drilled (Stearns and Vaksvik, 1935). More than half of the wells drilled by 1930 were for sugarcane irrigation and related operations, and about 60 to 65 wells were for irrigation of rice (Stearns and Vaksvik, 1935). In 1930, about 20 wells were used for irrigation of bananas, and about 5 wells were used for irrigation of taro (Stearns and Vaksvik, 1935). By 1985, a total 1,635 known wells, tunnels, and shafts had been drilled on Oahu for ground-water development (Nichols and others, 1996). Of this total, 383 were for irrigation, 247 were for public supply, 205 were for other uses, and 800 were either unused or abandoned (Nichols and others, 1996). By April 2002, the total number of wells, tunnels, and shafts on Oahu had increased to 2,077 (State Commission on Water Resource Management well index, unpub. data, 2002).

Between 1880 and 1980, withdrawals of ground water from the volcanic-rock aquifers of Oahu generally increased because of expanding sugarcane cultivation and urban development. Significant withdrawal of ground water for sugarcane irrigation started during the early 1890’s following the drilling of wells on the Ewa plantation (Stearns and Vaksvik, 1935; Mink, 1980). Most of the early withdrawals for public supply were from the Honolulu area, the main population center on the island. Although early information on total ground-water withdrawals on Oahu is incomplete, available records indicate that during 1910 about 153 Mgal/d was pumped from the volcanic-rock aquifers (Nichols and others, 1996). During the period 1971 through 1980, ground-water pumpage from the volcanic-rock aquifers of Oahu averaged about 361 Mgal/d (Nichols and others, 1996). In general, more than 85 percent of the total islandwide pumping from the volcanic-rock aquifers has been from the central Oahu area.

Additional ground water is developed by free-flowing artesian wells in coastal areas. In 1911, measured discharge from 29 free-flowing artesian wells in the Pearl Harbor area was 24.3 Mgal/d, and measured discharge from 35 free-flowing wells in Honolulu was 30.8 Mgal/d (Martin and Pierce, 1913). Discharge from the free-flowing artesian wells is dependent on the hydraulic head in the aquifer. For example, in May 1966, the Honolulu Board of Water Supply measured discharge of 20.75 Mgal/d from 31 free-flowing wells in the Pearl Harbor area when measured water levels in the wells ranged from 15.75 to 22.71 ft above mean sea level. In contrast, during September 1973, total discharge from 30 of the 31 wells previously measured in May 1966 was only 5.92 Mgal/d, and measured water levels in the wells ranged from 10.75 to 11.34 ft above mean sea level.

In addition to ground water pumped from the volcanic-rock aquifers using wells and shafts, ground water also is withdrawn from sedimentary aquifers using wells and from dike-impounded ground-water bodies using tunnels. Ground water withdrawn from coastal sedimentary deposits generally is brackish. In the southern Oahu coastal area west of Pearl Harbor, ground water in the sedimentary deposits is used for irrigation and industrial purposes. From 1930 to the early 1990's, annual mean ground-water withdrawals from the coastal sedimentary deposits in southwestern Oahu for sugarcane irrigation generally ranged from about 10 to 30 Mgal/d (George A.L. Yuen and Associates, Inc., 1989; Bauer, 1996).

Ground water from mountain tunnels that penetrate the dike-impounded ground-water body is used for irrigation and public supply. The Waiahole tunnel system (see next section), supplied more than 20 Mgal/d of dike-impounded ground water for sugarcane irrigation prior to the closure of Oahu Sugar Co. in 1995. The Honolulu Board of Water Supply continues to use water from tunnels for public supply. Annual reports from the Honolulu Board of Water Supply indicate that withdrawals from tunnels on Oahu during the 1980's and 1990's averaged about 10 to 20 Mgal/d, with most of the water developed in windward Oahu.

Surface Water

The main surface-water diversion systems on Oahu were the Waiahole tunnel and ditch system and the Wahiawa collection system, although other smaller systems and private diversions also were constructed (fig. 21). Construction of the Waiahole tunnel system was started in February 1913; the tunnel was originally designed to transport water from streams in windward Oahu to southwestern Oahu for sugarcane cultivation. The Waiahole tunnel system consists of 37 stream intakes connected by tunnels bored through ridges and spurs in windward Oahu, a main transmission tunnel through the Koolau Range, and additional tunnels and ditches in central Oahu that delivered water to sugarcane fields in southwestern Oahu (Wilcox, 1996). During the 1920's and 1930's, four successful water-development tunnels (Waikane 1, Waikane 2, Kahana, and Uwau) were added to the Waiahole tunnel system to collect dike-impounded ground water (Takasaki and Mink, 1985). The Uwau tunnel was later extended in the 1960's. Two additional tunnels were dry when excavated or shortly thereafter (Stearns and Vaksvik, 1935). Following the closure of Oahu Sugar Co. in 1995, the Waiahole system continued to divert about 23 Mgal/d of water (about 21 Mgal/d ground water and 2 Mgal/d surface water) from windward Oahu to leeward Oahu (State of Hawaii, 2001a). Some of this water is currently (2003) being restored to streams in windward Oahu in response to instream-flow needs.

The Waialua Sugar Co. constructed four surface-water collection systems (Wahiawa, Helemano, Opaeula, and Kamananui) between 1900 and 1906 (Wilcox, 1996). Data from 1960 through 1986 indicate that the surface-water collection systems diverted an average of about 33 Mgal/d, with the Wahiawa system accounting for about 25 Mgal/d of the total.

Recent Trends in Water Use

The first known comprehensive water-use inventory for Oahu was made for the years 1953 through 1957 (Hawaii Water Authority, 1959). During 1955, total ground-water use averaged 418 Mgal/d, and total surface-water use averaged 82 Mgal/d. About 360 Mgal/d of the total water used (500 Mgal/d) during 1955 was for irrigation, and about 60 Mgal/d was for domestic purposes (Hawaii Water Authority, 1959).

Since 1960, the U.S. Geological Survey has compiled annual water-use data for each state, including Hawaii, at 5-year intervals, although published data for Oahu are available only since 1975 (Nakahara, 1978, 1984; U.S. Geological Survey, 2002b; J.D. Nishimura, U.S. Geological Survey, written commun., 2003). The water-use compilations for the island of Oahu provide information on recent trends in ground-water and surface-water use for public-supply, agricultural, and other (for example industrial and commercial) purposes. The water-use compilations include data provided to the U.S. Geological Survey by the main water purveyors (government and private) and other water users, as well as information reported to the State Commission on Water Resource Management. It is possible that unreported water uses might have been excluded from the compilations. Furthermore, because the same individual did not always compile the data, data sources and interpretation may have varied from one compilation to the next. For example, it is unclear whether ground-water withdrawals from wells in non-volcanic rock aquifers, free-flowing artesian wells, and

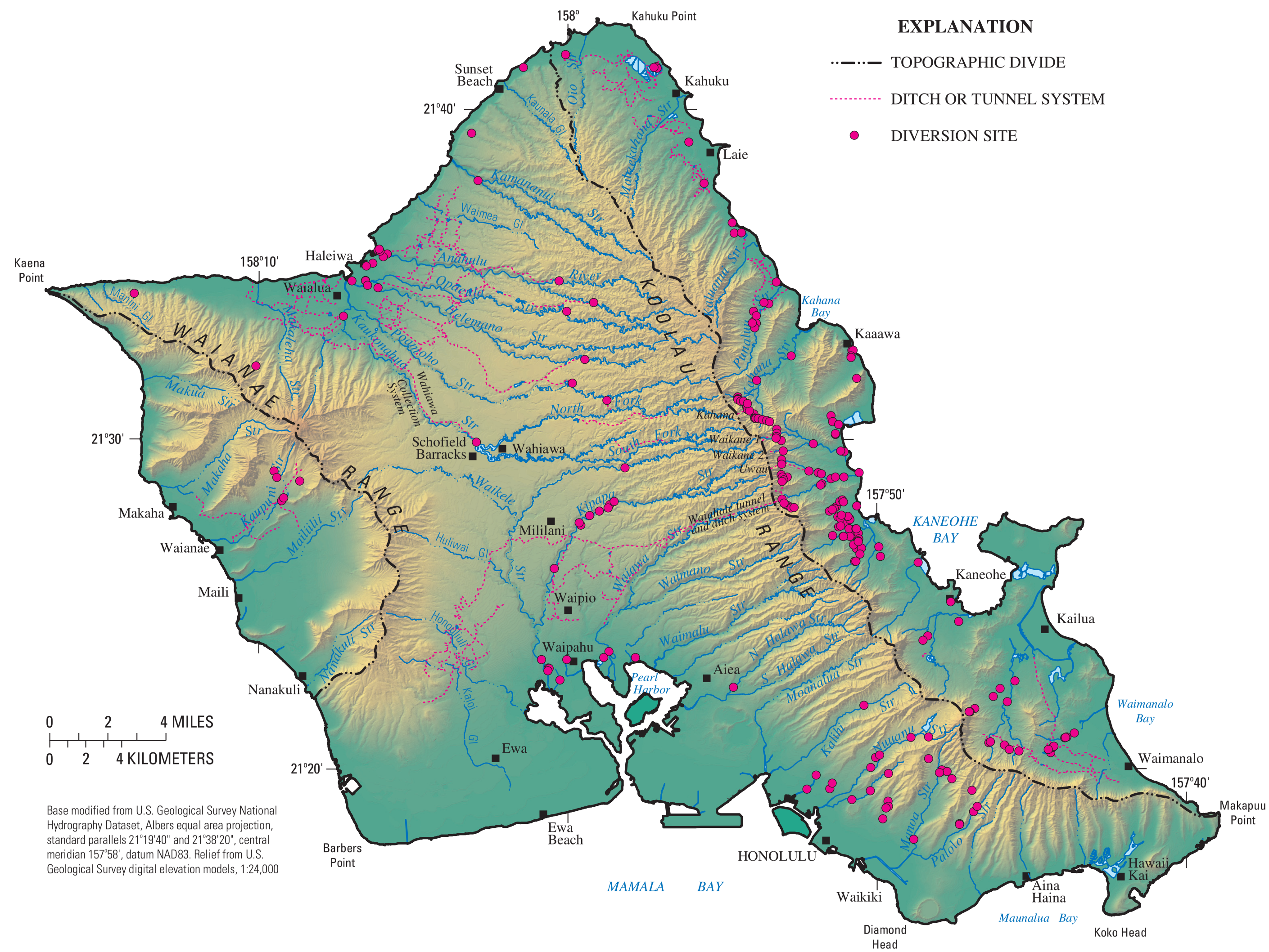


Figure 21. Surface-water diversion sites reported to the Hawaii Commission on Water Resource Management, island of Oahu, Hawaii (reported diversion sites from digital data, Hawaii Commission on Water Resource Management, 2002).

tunnels developing dike-confined ground water were consistently accounted for in each compilation. Because of the potential inconsistencies among compilations, only general trends are described below.

Although the population on Oahu increased between 1970 and 2000 (fig. 16), overall water use on Oahu declined from 1975 to 2000 (fig. 22), mainly because of the decreased need for irrigation water by sugarcane growers. During 1975, estimated use of freshwater (ground water and surface water) on Oahu was 469 Mgal/d; during 2000, estimated use had decreased to 212 Mgal/d, which is less than half of the 1975 total. In general, about 90 percent of the freshwater used on Oahu was derived from ground-water sources.

Between 1975 and 2000, estimated use of ground water for agricultural (mainly irrigation) purposes on Oahu steadily declined, from 201 Mgal/d in 1975 to 23 Mgal/d in 2000 (fig. 22). During the 1970's, sugarcane growers began to convert from the furrow-irrigation method to the more efficient drip-irrigation method. During the 1990's, the two remaining sugarcane plantations on the island ceased operations, and water use on the island declined significantly (fig. 22).

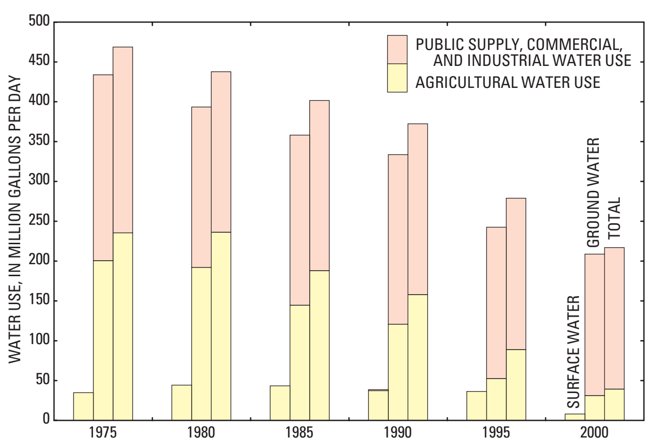


Figure 22. Water use from 1975 to 2000, island of Oahu, Hawaii (excluding saltwater used for thermoelectric power). Data from Nakahara (1978, 1984), U.S. Geological Survey (2002b), and Jill Nishimura (written commun., 2003).

Between 1975 and 1990, estimated use of ground water for nonagricultural purposes (public supply, commercial, and industrial) was greater than 200 Mgal/d. During 1995 and 2000, nonagricultural ground-water uses respectively were 190 and 180 Mgal/d. Since 1990, nonagricultural water use apparently decreased in spite of increases in population. The reduction in water use may reflect decreased demand and may be related to implementation of water-conservation measures (for example, reducing leaks, using low-flush toilets, wastewater reuse, and landscaping with water-efficient plants). However, the apparent decrease in nonagricultural water use since 1990 also may reflect inconsistencies among water-use compilations.

EFFECTS OF NATURAL AND HUMAN-RELATED FACTORS ON WATER QUALITY AND AQUATIC BIOTA

Both natural and human-related factors affect surface- and ground-water quality and the distribution and abundance of aquatic biota on Oahu. Natural factors that may affect water quality include geology, soils, vegetation, rainfall, ocean-water quality, and air quality. Human-related factors associated with urban and agricultural land uses also may affect water quality. The USEPA maintains a list of sites that represent potential sources of contamination of surface and ground water on Oahu, including sites with reported release of toxic compounds to the environment, sites that discharge wastewater to water bodies, and sites with reported hazardous-waste activities (fig. 23).

Rainfall

Rainfall is the main source of freshwater on Oahu and, thus, rainwater quality affects both surface- and ground-water quality. Because the main source of water and condensing nuclei for rainfall is the ocean, the dissolved inorganic constituents of rainwater mainly are from the ocean (Woodcock and Blanchard, 1955; Visher and Mink, 1964; Swain, 1973). Other sources of dissolved constituents include atmospheric gases and airborne dust. Windblown dust from Asia is a possible source of quartz and other constituents, and vapors and dust from urban and agricultural areas may be a source of organic contaminants.

The pH of rainwater on Oahu is acidic, with values generally ranging from about 4.2 to 5.0 (Dugan and Ekern, 1984). These rainwater pH values are similar to pH values of cloud-water samples collected around the Hawaiian islands (Parungo and others, 1982). Information from the island of Hawaii indicates that pH of

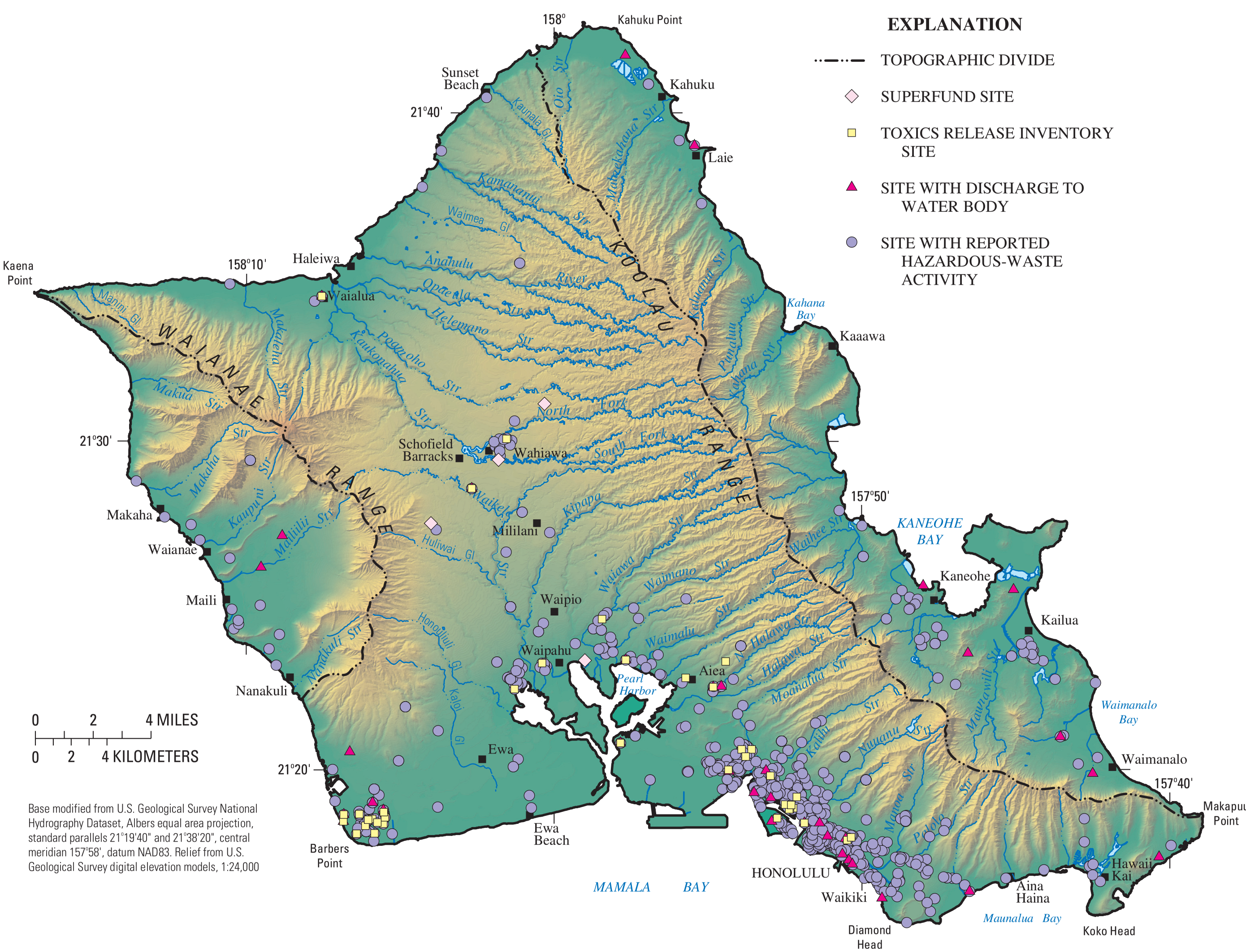


Figure 23. U.S. Environmental Protection Agency superfund sites, toxics release inventory sites, sites that discharge to a water body, and sites with reported hazardous-waste activity (site locations from U.S. Environmental Protection Agency, 2002a).

rainwater samples collected at the surface generally decreases with altitude, averaging about 5.2 at sea level to 4.3 at altitudes above 8,200 ft (Miller and Yoshinaga, 1981). Miller and Yoshinaga (1981) attributed the acidity in Hawaiian rainwater mainly to sulfuric acid. Although local volcanic eruptions contribute to the acidity, the effects of volcanic eruptions on rainfall pH generally decrease significantly beyond a distance of about 6 mi (Harding and Miller, 1982). The low pH values of rainwater may be from acidic materials derived from the ocean or transported over long distances in the midtroposphere (Miller and Yoshinaga, 1981; Parungo and others, 1982).

Sodium and chloride are the main dissolved constituents in both ocean water and rainwater (Swain, 1973), although sulfate may be the major anion present in rainwater near or downwind from areas of volcanic activity (Harding and Miller, 1982; Dugan and Ekern, 1984). Chemical analyses of cloud-water samples collected around the Hawaiian islands indicated that sodium, chloride, and sulfate ion molar concentrations were more than an order of magnitude higher than ammonium, nitrate, and calcium ion molar concentrations (Parungo and others, 1982). The cloud-water samples also had higher molar ratios (by more than an order of magnitude) of sulfate to chloride and sulfate to sodium than ocean water (Parungo and others, 1982).

In general, chloride concentration in rainwater samples collected at the surface decreases with altitude and distance from the ocean (Eriksson, 1957; Dugan and Ekern, 1984). Chloride concentrations in rainwater samples from Oahu generally range from a few to a few tens of milligrams per liter (mg/L) (Stearns and Vaksvik, 1935; Visher and Mink, 1964; Dugan and Ekern, 1984). Sulfate concentrations of rainwater samples on Oahu generally are a few milligrams per liter, although concentrations may be higher during periods when southerly winds transport volcanic gases from the island of Hawaii (Fox and others, 1965; Dugan and Ekern, 1984).

Rainwater samples from five sites on Oahu had median concentrations of total nitrogen ranging from 0.17 to 0.73 mg/L (Dugan and Ekern, 1984). Organic nitrogen was found to be a significant component of the total nitrogen in the rainwater samples from Oahu, with median concentrations ranging from 0.07 to 0.24 mg/L (Dugan and Ekern, 1984). On the basis of data from two sites in Manoa Stream valley, Dugan and Ekern (1984) estimated the annual organic nitrogen loading from rainfall to range from 1.35 to 3.92 lb/acre.

Bevenue and others (1972b) detected organochlorine pesticides (chlordane, DDT, dieldrin, lindane, and pentachlorophenol) in rainwater samples from both windward and leeward sites on Oahu. Concentrations of chlordane, DDT, dieldrin, and lindane generally were less than 0.01 micrograms per liter (μg/L), although the concentration of dieldrin in one sample from Honolulu was 0.097 μg/L. Pentachlorophenol concentrations ranged from 0.002 to 0.284 μg/L. Bevenue and others (1972b) indicated that organochlorine concentrations of rainwater samples were higher in the Honolulu area than in the windward and central Oahu areas during the early 1970's. The pesticides may have been carried into the atmosphere either as vapors or by occlusion on dust particles, and were subsequently removed from the atmosphere by rainfall (Bevenue and others, 1972b).

Surface Water

The chemical composition of surface water is dependent on rainwater and ground-water quality, geology, soils, vegetation, wildlife and livestock, waste discharges, applied nutrients and pesticides, and other factors. Because the factors that control rainwater quality also can affect surface-water quality, human-related factors that affect air quality may affect surface-water quality in areas upstream from, but downwind of, urban and agricultural activities. Thus, information on surface-water quality in areas upstream from urban and agricultural activities may not reflect the background surface-water quality completely unaffected by human activities.

Natural Factors

Insofar as they are unaffected by human activities, natural factors that can affect surface-water quality include rainfall, ground-water discharge, geology, soils, and vegetation. During large storms, suspended-sediment concentrations in streams can increase significantly to concentrations exceeding 1,000 mg/L (Doty and others, 1981; Shade, 1984; Hill, 1996). The suspended sediments are mainly clay- and silt-sized particles derived from erosion of soils and lead to increased turbidity of water in streams during storms (Yim and Dugan, 1975; Shade, 1984; DeVito and others, 1995). Annual suspended-sediment yields from streams in undeveloped areas on Oahu may range from less than 100 to more than 1,000 tons per square mile (Hill, 1996; Shade, 1984; Doty and others, 1981; Jones and others, 1971). Organic and inorganic constituents that are attached to suspended sediments can increase the quantity of these constituents in runoff (see for example Yim and Dugan, 1975; Beltran and others, 2002).

At a given site in a stream during a storm, the time of peak concentration of suspended sediments in the stream water commonly occurs at or lags behind the time of peak discharge (Matsushita and Young, 1973; Shade, 1984). However, in some places, the time of peak concentration of suspended sediments may precede the time of peak discharge (Tomlinson and De Carlo, 2003) because the first flush of easily eroded material may occur during the early part of the storm. The relative timing of the peaks in concentration and discharge is affected by factors including antecedent rainfall, rainfall intensity, duration, and distribution, geology, soils, slope, land cover, proximity of sediment sources, and the presence of man-made drainage ways.

During periods when direct runoff represents the main component of streamflow, the concentrations of most dissolved constituents in streams generally are reduced relative to the concentrations during low-flow conditions because of dilution by rainfall-induced runoff (Visher and Mink, 1964; Davis, 1969; Matsushita and Young, 1973). During high-flow conditions, the pH of stream water also may decrease because of the acidity of rainfall on Oahu (Dugan and Ekern, 1984; DeVito and others, 1995). Some dissolved constituents in streams may have higher concentrations during high-flow conditions if those constituents are transported in significant quantities by runoff to streams (see for example Hoover, 2002).

The volcanic rocks and soils at the surface are a source of numerous inorganic constituents in stream water. For example, most of the silica in stream water is derived from the volcanic rocks and soil (Visher and Mink, 1964; Davis, 1969). Calcium, magnesium, sodium, and potassium in stream water generally are derived from volcanic rocks, although these constituents also may be derived partly from rain. Weathered volcanic rocks are a source of iron and aluminum in stream water. Whereas the concentrations of dissolved iron and aluminum in stream water generally are less than a few hundred micrograms per liter, the concentrations of total iron and aluminum may exceed thousands of micrograms per liter, reflecting the input from suspended material derived from soils and weathered volcanic rocks.

Heavy metals in stream water also may be derived from volcanic rocks and soil (Lau and others, 1973; Halbig and others, 1985; McMurtry and others, 1995; De Carlo and Spencer, 1995). Storm runoff samples collected from a forested part of Manoa Stream valley were analyzed to determine the concentrations of selected metals (Yim and Dugan, 1975). Cadmium, chromium, and mercury were not detected, although they may have been present at concentrations below the analytical limit of detection, which was not specified. Reported median concentrations of dissolved copper, nickel, and zinc respectively were 0.014, 0.029, and 0.019 mg/L, and reported median concentrations of total copper and nickel respectively were 0.113 and 0.103 mg/L (Yim and Dugan, 1975). The reported median dissolved copper and nickel concentrations are greater than the current criteria for streams in Hawaii (table 7).

Chloride in stream water generally is not derived from the volcanic rocks (Visher and Mink, 1964), but may be from rain or ground-water discharge. Where streams flow over noncalcareous rocks and sediments, bicarbonate mainly is derived from decaying vegetation in the soil (Visher and Mink, 1964; Davis, 1969). Where streams flow over calcareous rocks, bicarbonate may be derived from dissolution of the rock material.

Nutrients in stream water may exist in both dissolved and particulate forms and, in natural settings unaffected by anthropogenic activities, are derived from various sources. Nitrogen may be derived from rainfall, fixation of atmospheric nitrogen by leguminous plants and root- and leaf-nodulating nonleguminous plants, and nonsymbiotic fixation by azofication (Yim and Dugan, 1975). Organic nitrates (alkyl nitrates) in the atmosphere may be derived from the ocean (Chuck and others, 2002), and may represent a natural source of nitrogen in stream water. Phosphate may be derived from the weathering of volcanic rocks containing the mineral apatite (Visher and Mink, 1964) or from Asian dust (Kurtz and others, 2001).

Both Hoover (2002) and DeVito and others (1995) collected surface-water samples from generally undeveloped areas on Oahu. Hoover (2002) indicated that concentrations of dissolved nitrogen (total dissolved nitrogen, dissolved organic nitrogen, nitrate, and

Table 7. Hawaii water-quality criteria for freshwater, saltwater, and fish consumption (Hawaii Administrative Rules, Title 11, Department of Health, Chapter 54, Water Quality Standards)

[all values in micrograms per liter; ns, no standard has been developed; values for metals refer to the dissolved fraction; for compounds listed in the plural in the "Contaminant" column, values listed to the right of these compounds refer to the total allowable concentration of any combination of isomers of the compound, not only to concentrations of individual isomers; see footnote for further information]

Contaminant	Freshwater[1]		Saltwater[1]		Fish consumption[2]
	Acute[2]	Chronic[2]	Acute[2]	Chronic[2]	
Acenapthene	570	ns	320	ns	ns
Acrolein	23	ns	18	ns	250
Acrylonitrile*	2,500	ns	ns	ns	0.21
Aldrin*	3	ns	1.3	ns	0.000026
Aluminum	750	260	ns	ns	ns
Antimony	3,000	ns	ns	ns	15,000
Arsenic	360	190	69	36	ns
Benzene*	1,800	ns	1,700	ns	13
Benzidine*	800	ns	ns	ns	0.00017
Beryllium*	43	ns	ns	ns	0.038
Cadmium	3+	3+	43	9.3	ns
Carbon tetrachloride*	12,000	ns	16,000	ns	2.3
Chlordane*	2.4	0.0043	0.09	0.004	0.000016
Chlorine	19	11	13	7.5	ns
Chloroethers-					
ethy(bis-2)*	ns	ns	ns	ns	0.44
isoprophyl	ns	ns	ns	ns	1,400
methyl(bis)*	ns	ns	ns	ns	0.0006
Cloroform*	9,600	ns	ns	ns	5.1
Chlorophenol(2)	1,400	ns	ns	ns	ns
Chlorpyrifos	0.083	0.041	0.011	0.0056	ns
Chromium (VI)	16	11	1,100	50	ns
Copper	6+	6+	2.9	2.9	ns
Cyanide	22	5.2	1	1	ns
DDT*	1.1	0.001	0.013	0.001	0.000008
DDT metabolite TDE*	0.03	ns	1.2	ns	ns
Demeton	0.1	ns	0.1	ns	
Dichloro-					
benzenes*	370	ns	660	ns	850
benzidine*	ns	ns	ns	ns	0.007
ethane(1,2)*	39,000	ns	38,000	ns	79
ethylene(1,1)*	3,900	ns	75,000	ns	0.6
phenol(2,4)	670	ns	ns	ns	ns
propanes	7,700	ns	3,400	ns	ns
propene(1,3)	2,000	ns	260	ns	4.6
Dieldrin*	2.5	0.0019	0.71	0.0019	0.000025
Dinitro-					
o-cresol(2,4)	ns	ns	ns	ns	250
toluenes*	110	ns	200	ns	3
Dioxin*	0.003	ns	ns	ns	$5.0x10^{-9}$
Diphenylhydrazine(1,2)	ns	ns	ns	ns	0.018
Endosulfan	0.22	0.056	0.034	0.0087	52
Endrin	0.18	0.0023	0.037	0.0023	ns
Ethylbenzene	11,000	ns	140	ns	1,070
Fluoranthene	1,300	ns	13	ns	18
Guthion	ns	0.01	ns	0.01	ns
Heptachlor*	0.52	0.0038	0.053	0.0036	0.00009
Hexachloro-					
benzene*	ns	ns	ns	ns	0.00024
butadiene*	30	ns	11	ns	16
cyclohexane-					
*α**	ns	ns	ns	ns	0.01
*β**	ns	ns	ns	ns	0.018
technical*	ns	ns	ns	ns	0.014
cyclopentadiene	2	ns	2	ns	ns
ethane*	330	ns	310	ns	2.9
Isophorone	39,000	ns	4,300	ns	170,000
Lead	29+	29+	140	5.6	ns
Lindane*	2	0.08	0.16	ns	0.02
Malathion	ns	0.1	ns	0.1	ns

Table 7. Hawaii water-quality criteria for freshwater, saltwater, and fish consumption (Hawaii Administrative Rules, Title 11, Department of Health, Chapter 54, Water Quality Standards)--Continued

[all values in micrograms per liter; ns, no standard has been developed; values for metals refer to the dissolved fraction; for compounds listed in the plural in the "Contaminant" column, values listed to the right of these compounds refer to the total allowable concentration of any combination of isomers of the compound, not only to concentrations of individual isomers; see footnote for further information]

Contaminant	Freshwater[1]		Saltwater[1]		Fish consumption[2]
	Acute[2]	Chronic[2]	Acute[2]	Chronic[2]	
Mercury	2.4	0.55	2.1	0.025	0.047
Methoxychlor	ns	0.03	ns	0.03	ns
Mirex	ns	0.001	ns	0.001	ns
Naphthalene	770	ns	780	ns	ns
Nickel	5+	5+	75	8.3	33
Nitrobenzene	9,000	ns	2,200	ns	ns
Nitrophenols*	77	ns	1,600	ns	ns
Nitrosamines*	1,950	ns	ns	ns	0.41
Nitroso					
dibutylamine-*N**	ns	ns	ns	ns	0.19
diethylamine-*N**	ns	ns	ns	ns	0.41
dimethylamine-*N**	ns	ns	ns	ns	5.3
diphenylamine-*N**	ns	ns	ns	ns	5.3
pyrrolidine-*N**	ns	ns	ns	ns	30
Parathion	0.065	0.013	ns	ns	ns
Pentachloro-					
ethanes	2,400	ns	130	ns	ns
benzene	ns	ns	ns	ns	28
phenol	20	13	13	ns	ns
Phenol	3,400	ns	170	ns	ns
2,4-dimethyl	700	ns	ns	ns	ns
Phthalate esters					
dibutyl	ns	ns	ns	ns	50,000
diethyl	ns	ns	ns	ns	590,000
di-2-ethylhexyl	ns	ns	ns	ns	16,000
dimethyl	ns	ns	ns	ns	950,000
Polychlorinated biphenyls*	2	0.014	10	0.03	0.000079
Polynuclear aromatic hydrocarbons*	ns	ns	ns	ns	0.01
Selenium	20	5	300	71	ns
Silver	1+	1+	2.3	ns	ns
Tetrachloro-					
ethanes	3,100	ns	ns	ns	ns
benzene(1,2,4,5)	ns	ns	ns	ns	16
ethane(1,1,2,2)*	ns	ns	3,000	ns	3.5
ethylene*	1,800	ns	3,400	145	2.9
phenol(2,3,5,6)	ns	ns	ns	440	ns
Thallium	470	ns	710	ns	16
Toluene	5,800	ns	2,100	ns	140,000
Toxaphene*	0.73	0.0002	0.21	0.0002	0.00024
Tributyltin	ns	0.026	ns	0.1	ns
Trichloro-					
ethane(1,1,1)	6,000	ns	10,400	ns	340,000
ethane(1,1,2)*	6,000	ns	ns	ns	14
ethylene*	15,000	ns	700	ns	26
phenol(2,4,6)*	ns	ns	ns	ns	1.2
Vinyl chloride*	ns	ns	ns	ns	170
Zinc	22+	22+	95	86	ns

*Carcinogen

+The value listed is the minimum standard. Depending upon the receiving water $CaCO_3$ hardness, higher values may be calculated using the respective formula in the U.S. Environmental Protection Agency publication Quality Criteria for Water (EPA 440/5-86-001, Revised May 1, 1987).

[1]Freshwater standards apply where the dissolved inorganic ion concentration is less than 0.5 parts per thousand; saltwater standards apply where the dissolved inorganic ion concentration is greater than 0.5 parts per thousand.

[2]All state waters shall be free from contaminants in concentrations that exceed the acute standards; all state waters shall be free from contaminants in concentrations that, on average during any 24-hour period, exceed the chronic standards; all state waters shall be free from contaminants in concentrations that, on average during any 30-day period, exceed the consumption standards for non-carcinogens; all state waters shall be free from contaminants in concentrations that, on average during any 12-month period, exceed the consumption standards for contaminants identified as carcinogens.

ammonia) generally increased with increasing stream discharge, although concentrations of total dissolved phosphorus and dissolved phosphate were poorly correlated with discharge. DeVito and others (1995) indicated that nitrate and total phosphorus concentrations increased with stream discharge, whereas organic nitrogen and dissolved phosphorus concentrations were poorly correlated with discharge. Because phosphate is retained by goethite and, to a lesser extent, other iron and aluminum oxides and hydroxides (Parfitt and others, 1975; McLaughlin and others, 1981; Barron and others, 1988) that are common in Hawaiian soils, total phosphorus concentrations generally increase with increasing suspended-sediment concentrations (Hoover, 2002; DeVito and others, 1995; Yim and Dugan, 1975).

Yim and Dugan (1975) collected storm runoff samples from a forested, interior part of Manoa Stream valley during 1974–75, and reported median concentrations of total Kjeldahl, nitrate plus nitrite, and total nitrogen of 2.10, 0.03, and 2.21 mg/L, respectively. Median orthophosphate and total phosphate concentrations, respectively, were 0.00 and 0.86 mg/L (Yim and Dugan, 1975). Total nitrogen and total phosphorus concentrations were found to be correlated with the suspended-sediment concentrations in the runoff samples, and are greater than current criteria for streams in Hawaii (table 8).

In areas where ground water discharges to streams, the quality of the ground water controls surface-water quality during periods of low flow. For example, dike-impounded ground water in the Koolau Range has a silica concentration of about 15 to 25 mg/L, which is similar to the silica concentrations of streams in windward Oahu that receive ground-water discharge from the dike-impounded system (see for example figure 24, gaging stations 16275000, 16284200, and 16296500) (Davis, 1969; Lau and others, 1973).

Where ground-water discharge to streams is significant, the dissolved solids concentrations in surface water may be high relative to where streams do not receive ground-water discharge. For example, the chloride concentrations of water collected from Waikele Stream (stream gaging station 16213000), which receives ground-water discharge from the freshwater-lens system, were higher than in water collected from Kalihi Stream (gaging stations 16219300), which is not affected by ground-water discharge from the freshwater-lens system (fig. 24) (Yee and Lum, 1993). The concentrations of dissolved constituents in streams that receive ground-water discharge generally are lower in wetter areas, where evapotranspiration is low (Visher and Mink, 1964). In areas where the evapotranspiration rate is high, concentrations of dissolved constituents in recharge water that discharges to streams may be increased relative to rain water because water that is lost to the atmosphere by evapotranspiration does not remove the dissolved constituents. This may partly explain the relatively high concentrations of dissolved

Table 8. Hawaii water-quality criteria for streams (Hawaii Administrative Rules, Title 11, Department of Health, Chapter 54, Water Quality Standards)

[µg/L, micrograms per liter; mg/L, milligrams per liter]

Parameter	Geometric mean not to exceed the given value	Not to exceed the given value more than ten percent of the time	Not to exceed the given value more than two percent of the time
Wet season (November 1 through April 30)			
Total nitrogen (µg/L)	0.25	0.52	0.80
Nitrate plus nitrite nitrogen (µg as nitrogen/L)	0.07	0.18	0.30
Total phosphorus (µg/L)	0.05	0.10	0.15
Total suspended solids (mg/L)	20.0	50.0	80.0
Turbidity (nephelometric turbidity units)	5.0	15.0	25.0
Dry season (May 1 through October 31)			
Total nitrogen (µg/L)	0.18	0.38	0.60
Nitrate plus nitrite nitrogen (µg as nitrogen/L)	0.03	0.09	0.17
Total phosphorus (µg/L)	0.03	0.06	0.08
Total suspended solids (mg/L)	10.0	30.0	55.0
Turbidity (nephelometric turbidity units)	2.0	5.5	10.0

pH shall not deviate more than 0.5 units from ambient conditions and shall not be lower than 5.5 nor higher than 8.0.
Dissolved oxygen shall not be less than 80 percent of saturation, determined as a function of the ambient water temperature.
Temperature shall not vary more than one degree Celsius from ambient conditions.

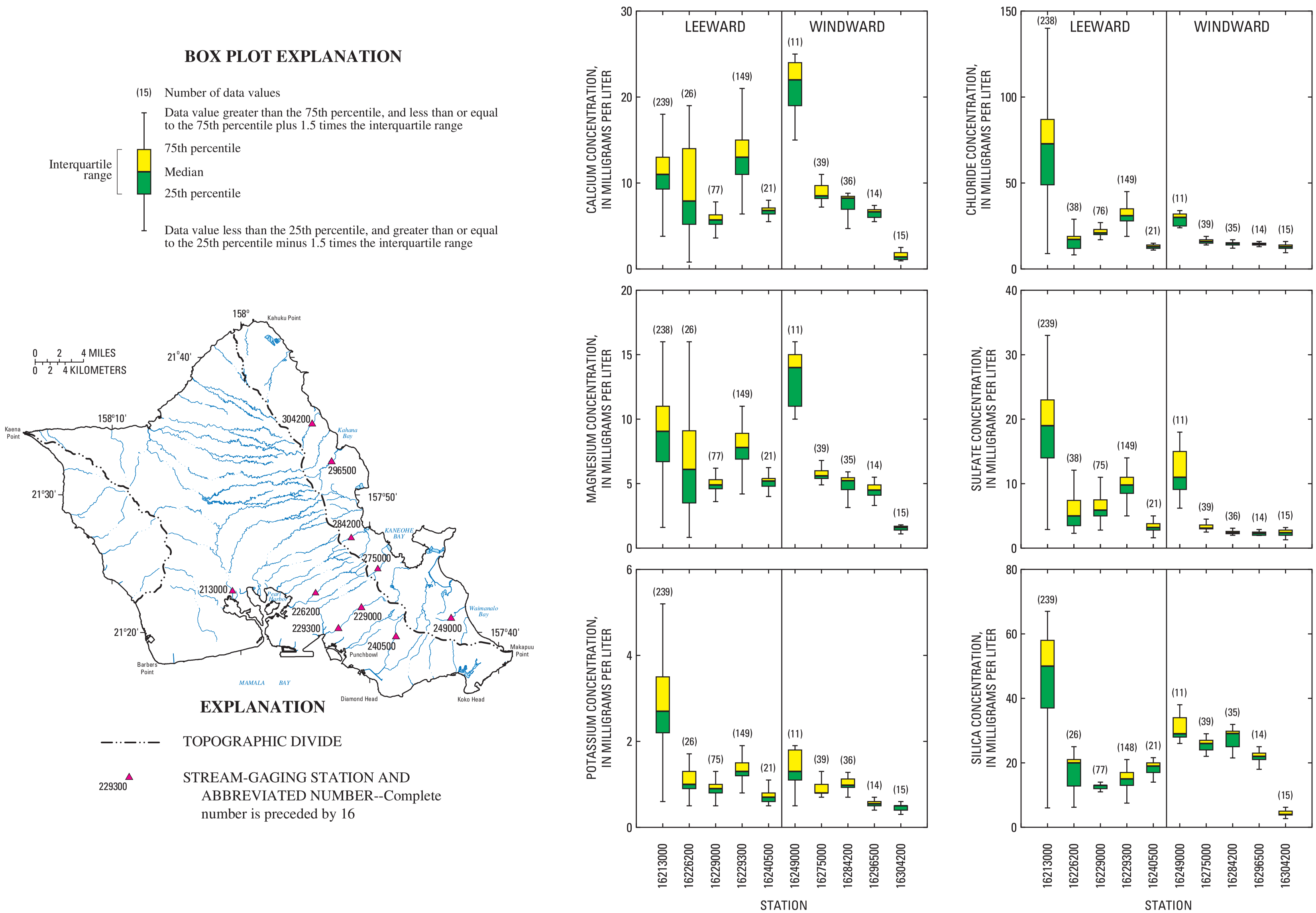


Figure 24. Concentrations of selected major constituents dissolved in surface-water samples from streams, island of Oahu, Hawaii. Box plots are based on U.S. Geological Survey data collected from 1969 to 2001.

constituents in stream-water samples from the Waimanalo area of eastern Oahu (fig. 24, gaging station 16249000), where evapotranspiration rates are high.

Chlorinated organic compounds in the environment generally are attributed to human uses of chemicals, although they also may be produced by biotic and abiotic processes in the environment (Myneni, 2002). Chlorinated organic compounds may be formed at rapid rates from the transformation of inorganic chlorine during humification of plant material (Myneni, 2002). Widespread chlorination of organic compounds in humic materials may account for the presence of organochlorine compounds in unpolluted environments (Casey, 2002).

Fecal-indicator bacteria (total coliform, fecal coliform, *Escherichia coli*, and fecal streptococci) commonly are found in the soil in Hawaii (Hardina and Fujioka, 1991; Fujioka and Yoneyama, 2001). Because soil commonly is transported to streams during periods of rainfall, the soil represents a natural source of fecal-indicator bacteria in streams.

Urban-Related Factors

Urbanization can affect surface-water quality in a variety of ways: wastewater discharges into streams can lead to increased nutrient concentrations of stream water (Aoyama and Young, 1974; Dugan, 1977; Manglallan, 1994); construction activities can increase the suspended-sediment load in streams (Hill, 1996; Wong and Yeatts, 2002); and storm runoff may contain constituents that affect stream-water quality, including metals such as lead, cadmium, copper, and zinc (Lau and others, 1976; Yamane and Lum, 1985; De Carlo and Spencer, 1995; Sutherland and Tolosa, 2001; Presley, 2001; Presley, 2002; Beltran and others, 2002; De Carlo and Anthony, 2002), oil and grease (Fujiwara, 1973; Dugan, 1977; Yamane and Lum, 1985; Wong and Hill, 1992; City and County of Honolulu, 2001; Presley, 2002), pesticides (Bevenue and others, 1972a; Matsushita and Young, 1973; Young and others, 1976; Lau and others, 1976; Yamane and Lum, 1985; Wong and Hill, 1992; Taogoshi and others, 2001, 2002), polycyclic aromatic hydrocarbons (Taogoshi and others, 2001), and nutrients (Quan and others, 1970; Chun and others, 1972; Young and others, 1972; Matsushita and Young, 1973; Lau and others, 1976; Hoover, 2002).

Paved areas, storm sewers, channelized streams, and surface-water detention systems in urban areas can affect the timing of peaks in discharge and water-quality constituent concentrations during a storm (Matsushita and Young, 1973; Yamane and Lum, 1985). In urban areas, the presence of paved areas and storm-water collection systems may cause water-quality constituent concentrations in streams to peak before the peak discharge during a storm because of a first-flush effect (Yamane and Lum, 1985). Presley (2002) collected water samples at 2- to 7-minute intervals from a storm drain that receives runoff from a highway in Halawa Stream valley during April 2002, and the peak concentrations (total) of cadmium, copper, lead, and zinc in the water samples occurred before the peak discharge.

In Hawaii, naturally occurring lead concentrations in soils and streambed sediments rarely exceed about 25 to 40 parts per million (ppm), and commonly are much lower. In urban areas on Oahu, however, lead concentrations in soils and sediments can exceed 100 ppm (De Carlo and Spencer, 1995; McMurtry and others, 1995; Sutherland, 2000; Sutherland and Tack, 2000; De Carlo and Anthony, 2002), and lead concentrations in excess of 1,000 ppm were detected in material collected from streets in residential and commercial areas on Oahu (Lau and others, 1976). Concentrations of lead and other trace elements in sediments may be affected by the grain-size distribution of the sediments (Sutherland, 2000). Anthropogenic sources of lead in Hawaii include gasoline that contained a lead additive, leaded paint from older homes, batteries, plumbing fixtures, and pesticides (Spencer and others, 1995). Automotive emissions are the largest source of lead in soils and sediments on Oahu (De Carlo and Spencer, 1995; McMurtry and others, 1995; Spencer and others, 1995; Sutherland and Tolosa, 2000, 2001; Sutherland and Tack, 2000). Anthropogenic inputs of lead to the environment have decreased with the decrease in use of lead additives to fuels, although substantial amounts of lead may remain in soils in urban areas on Oahu (De Carlo and Anthony, 2002).

Dissolved lead in surface water generally is detected at concentrations of less than a few to a few tens of micrograms per liter, although a dissolved lead concentration of 110 μg/L was detected in storm runoff from an urban area of central Oahu (Yamane and Lum, 1985). Total lead in surface water at a site can range from less than a few micrograms per liter to more than 100 μg/L, and generally is affected by the concentration of suspended sediment in the water.

Concentrations of lead and other metals in suspended particulate matter are variable during storms, and are affected by land use (Beltran and others, 2002).

Anthropogenic activities in urban areas can lead to enrichment of cadmium, zinc, and copper in soils and sediments on Oahu (Sutherland and Tolosa, 2001; De Carlo and Anthony, 2002). De Carlo and Anthony (2002) indicated that runoff from roads that are affected by automotive emissions and tire wear may be the main source of cadmium, zinc, and copper in sediments. Anthropogenic sources of cadmium in soils and sediments on Oahu include automobile tires, batteries, paints, plastics, photograph-processing materials, and plated iron products such as nuts and bolts (Yamane and Lum, 1985; McMurtry and others, 1995). Cadmium also may be derived from natural sources including volcanic rocks, volcanic emissions, and atmospheric dust. The concentration of dissolved cadmium detected in surface water generally is less than 10 μg/L, although the concentration of total cadmium exceeded 100 μg/L in storm runoff from an urban area of central Oahu (Yamane and Lum, 1985).

Zinc can be derived from wear of automobile tires, because zinc is widely used in the vulcanization of rubber (De Carlo and Spencer, 1995; Sutherland and Tack, 2000). Zinc also is an impurity of phosphate fertilizers (McMurtry and others, 1995). Dissolved zinc concentrations detected in surface water on Oahu range from less than a few micrograms per liter to more than 100 μg/L. Total zinc concentrations detected in surface water range from less than a few micrograms per liter to several hundred micrograms per liter.

Copper may be derived from various anthropogenic sources including copper-based insecticides and fungicides used in urban or agricultural areas (table 4). Dissolved copper concentrations detected in surface water on Oahu range from less than a few micrograms per liter to a few tens of micrograms per liter. Total copper concentrations detected in surface water generally are less than a few to a few tens of micrograms per liter, although a total copper concentration of 1,000 μg/L has been detected from Kalihi Stream in Honolulu.

Whereas the concentrations of metals such as lead, zinc, copper, barium, and cobalt in stream water may be elevated in urban areas, Beltran and others (2002) indicated that concentrations of nickel, vanadium, and chromium were similar in urban and conservation areas.

In developed (nonagricultural) areas, pesticides are used for home and garden, industrial, and governmental purposes. Pesticides used by private individuals and businesses (around homes, buildings, and other facilities, and on lawns and gardens), pest-control and wood-treating industries, and government agencies (around buildings, parking lots, and other facilities, on parks, forested areas, and shrubland, and along flood-control channels and roadways) may potentially be transported to streams in surface runoff.

Persistent organochlorine pesticides were commonly used in urban areas on Oahu in the past (table 4), and these pesticides and their degradation products have been detected in sediment and water from streams and storm runoff from urban areas on Oahu. Sediment samples from three streams (Manoa, Nuuanu, and Kaneohe) in urban areas on Oahu contained detectable concentrations of aldrin, dieldrin, chlordane, and DDT (or its degradation products) (Brasher and Anthony, 2000).

Water samples (unfiltered) collected during the period 1975 to 1982 by the USGS from Kalihi Stream (station 16229300), in urban Honolulu, contained the organochlorine pesticides chlordane (0.1 μg/L), dieldrin (0.01–0.48 μg/L), and heptachlor epoxide (0.01 μg/L). Aldrin, chlordane, dieldrin, endrin, heptachlor, DDT, and PCB also were detected in sediment samples from Kalihi Stream (station 16229300) at concentrations generally ranging from a few to a few hundred micrograms per kilogram (unpublished data from USGS water-quality database). Bevenue and others (1972a) detected DDD, DDT, and dieldrin in water samples (unfiltered) from Kalihi Stream at levels below 0.013 μg/L, and Matsushita and Young (1973) reported concentrations of chlordane, dieldrin, and DDE below 0.002 μg/L in water samples (unfiltered) from Kalihi Stream. A water sample collected from a ditch near a wood-treatment plant near Kalihi Stream contained pentachlorophenol (PCP) at a concentration of 1.143 μg/L, although the concentration was diluted to 0.168 μg/L in the stream (Bevenue and others, 1972a).

Water samples from two canals draining urban areas in Honolulu also contained detectable levels of DDD, DDT, dieldrin, lindane, and chlordane, with dieldrin detected at the highest level (0.0186 μg/L) (Bevenue and others, 1972a). Sediment samples collected from the two canals contained DDE, DDD, DDT, dieldrin, and chlordane, with chlordane detected at the highest level (0.72 ppm) (Bevenue and others, 1972a).

During 1976, material collected from streets in residential and commercial areas of windward Oahu contained residues of chlordane, dieldrin, and DDT at levels below 0.075 ppm (Lau and others, 1976). Water samples from streams in windward Oahu also contained detectable concentrations of chlordane, dieldrin, and DDT at levels below 0.05 µg/L (Lau and others, 1976; Young and others, 1976). Concentrations of organochlorine pesticides in stream-water samples generally were found to be higher during wet-weather conditions than dry-weather conditions probably because of the adsorbed phase on suspended sediments (Lau and others, 1976; Young and others, 1976).

Urban storm-water samples collected during 1980–82 from Mililani in central Oahu contained organochlorine insecticides and degradation products (aldrin, chlordane, DDE, dieldrin, heptachlor, heptachlor epoxide, lindane, and methoxychlor) as well as organophosphate insecticides (diazinon and malathion) and herbicides (2,4-D, 2,4,5-T, and silvex) (Yamane and Lum, 1985). Twenty-three pesticides (16 herbicides and 7 insecticides) were detected in water samples collected from Manoa Stream, which drains an urban area, as part of the NAWQA study. The most commonly detected herbicide was prometon, and the most commonly detected insecticides were dieldrin, diazinon, and carbaryl (L.D. Miller, U.S. Geological Survey, written commun., 2002). Most pesticides were detected more frequently in high-flow samples, although dieldrin, prometon, and imidacloprid were detected more frequently in low-flow samples from Manoa Stream (L.D. Miller, U.S. Geological Survey, written commun., 2002).

Organic compounds, including acetone, chloroform, benzene, toluene, styrene, and xylene, which are commonly associated with activities in urban areas, were detected in water samples from Manoa Stream generally at concentrations below 1 µg/L (Taogoshi and others, 2001). These compounds are found in numerous products including petroleum products, solvents, paints, packaging materials, and pesticides, although they also may be derived from natural sources (Agency for Toxic Substances and Disease Registry, 2002). Toluene also was detected in urban stormwater runoff samples from residential and commercial areas on Oahu at levels between 0.5 and 1.3 µg/L (City and County of Honolulu, 2001). Phenols were detected in storm runoff from residential, commercial, and industrial areas on Oahu at levels between about 10 and 20 µg/L (City and County of Honolulu, 2001).

Polycyclic aromatic hydrocarbons (PAHs) are organic compounds commonly formed during the incomplete burning of gasoline and other organic substances, and may enter the environment as releases to air from volcanoes, fires, and exhaust from automobiles. PAHs also may be found in creosote, tar, plastics, asphalt, and pesticides (Agency for Toxic Substances and Disease Registry, 2002). In the environment, PAHs tend to adsorb to sediments, soils, and particulate matter and tend to bioconcentrate in aquatic organisms. Various PAHs have been detected in storm runoff from a freeway on Oahu at levels below 1 µg/L (Taogoshi and others, 2001).

Urban storm runoff also can contribute nutrients to stream water. Hoover (2002) indicated that nitrogen in runoff from urban areas may be associated with atmospheric nitrogen oxides derived from combustion sources, primarily automobiles. Other sources of nutrients include fertilizer applications and waste discharges.

Nutrient concentrations in surface-water samples from streams may be related to stream discharge, land use, and constituent form (dissolved or particulate). Hoover (2002) compared dissolved nutrient concentrations for low- and high-flow conditions for streams in two urban areas on Oahu, and indicated that concentrations generally were higher in storm-runoff samples relative to low-flow samples. Streams in urban areas generally had higher concentrations of dissolved nutrients in storm-runoff samples than streams in undeveloped and agricultural areas on Oahu (Hoover, 2002).

Particulate organic carbon and particulate organic nitrogen concentrations in surface-water samples from Oahu generally decreased with increasing stream discharge, whereas a general relation between particulate phosphorus and stream discharge was not evident (Hoover, 2002). (Particulate constituent concentrations are expressed as the ratio of the constituent mass retained on a filter with a 1.2-micrometer pore size to the suspended-sediment mass.) The decrease of particulate organic carbon and particulate organic nitrogen concentrations with increasing discharge may reflect dilution of the detrital component of particulate concentrations at low flows with (1) increasing quantities of soil particles with a relatively constant nutrient composition, or (2) increasing quantities of soil particles eroded from deeper soil horizons or stream channels that are depleted in nutrients relative to surface soils (Hoover, 2002).

Streams in urban areas generally had higher concentrations of particulate inorganic phosphorus (expressed as the mass ratio of inorganic phosphorus to suspended sediment) in storm-runoff samples than streams in undeveloped and agricultural areas on Oahu (Hoover, 2002). Streams in urban and agricultural areas generally had slightly lower concentrations of particulate organic nitrogen and particulate organic carbon in storm-runoff samples than streams in undeveloped areas on Oahu (Hoover, 2002).

Water samples collected from six sites on Manoa Stream in urbanized Honolulu generally had higher total nitrogen and total phosphorus concentrations during wet-weather conditions relative to concentrations during dry-weather conditions (Ching, 1972; Chun and others, 1972). Water samples collected from four sites on Kalihi Stream generally had lower total nitrogen and higher total phosphorus concentrations during wet-weather conditions relative to concentrations during dry-weather conditions (Matsushita and Young, 1973). Streams in windward Oahu draining basins with greater urban development had higher total nitrogen concentrations than streams in less-developed areas (Lau and others, 1976).

Agriculture-Related Factors

Soil loss from agricultural areas is dependent on numerous factors including the amount and intensity of rainfall, soil condition, topography, and land use. Agricultural areas with a large proportion of roads can lead to greater soil loss (El-Swaify and Cooley, 1980). Because pineapple fields commonly have a higher proportion of road areas than sugarcane fields, soil loss from a pineapple field in central Oahu was found to be greater relative to loss measured after the field was converted to sugarcane (El-Swaify and Cooley, 1980). In sugarcane areas, significant soil loss can occur during periods when a field is bare or when the sugarcane is at an early stage of growth (El-Swaify and Cooley, 1980). Soil loss from agricultural fields may contribute to the suspended-sediment load in streams.

Nutrients associated with agricultural activities can be transported to streams. DeVito and others (1995) collected samples from two sites (one upstream of agricultural activity and the other within an agricultural area) on each of two streams in northern Oahu, and reported that concentrations of dissolved phosphorus, total phosphorus, and nitrate increased from upstream to downstream locations on each stream. Yim and Dugan (1975) collected runoff samples from sugarcane and pineapple fields in central Oahu and found lower pH values and higher total nitrogen concentrations associated with the runoff from the pineapple field. An animal feedlot may have contributed to high phosphorus concentrations measured in Waihee Stream relative to other streams in windward Oahu (Lau and others, 1976). Hoover (2002) indicated that streams in agricultural areas generally had higher concentrations of dissolved nutrients in base-flow samples than streams in undeveloped and urban areas on Oahu (Hoover, 2002), which may reflect the transport of agricultural fertilizers to ground water that discharges to streams.

Impurities in phosphate fertilizers are a source of metals, including zinc and cadmium (McMurtry, 1995), which may enter streams. De Carlo and Anthony (2002) also indicated that arsenic may be an impurity of fertilizers that can contribute to arsenic concentrations in sediments from streams on Oahu. Pesticides that contained mercury, copper, or arsenic and that were used in agricultural areas also are a source of trace elements that can affect the water- and sediment-quality of streams.

Annual amounts of herbicides applied on sugarcane and pineapple crops in Hawaii may be as much as five times the amounts applied in major temperate-region field crops (Green and others, 1977). The intensive use of herbicides, year-round cultivation practices, and proximity of agricultural lands to streams may enhance the possibility of pesticide transport to streams. Factors that control the amount of pesticides and fertilizers that may be transported to streams in runoff from agricultural lands include the amount and intensity of rainfall, antecedent rainfall or irrigation, topography, soil type and condition, crop type and practices, pesticide application rates and timing, and pesticide properties (rates of microbial and chemical degradation, adsorption and desorption characteristics, and volatility).

During 1973–74, unfiltered storm-runoff samples that were collected from areas draining sugarcane and pineapple fields in northern Oahu contained detectable levels of the herbicide diuron (Green and others, 1977). Diuron concentrations ranged from 3 to 74 μg/L in runoff samples from a sugarcane area, and 3 to 21 μg/L in runoff from a pineapple area. Diuron concentrations in sediment samples collected from streams in central Oahu ranged from 0.008 to 0.566 ppm, and concentrations of 3,4-dichloroaniline (DCA), which is a degradation product of diuron, ranged from nondetectable levels (0.02 ppm limit of detection) to 0.95 ppm (Green and others, 1977). Green and others (1977) did not detect atrazine and ametryn (0.05 ppm limit of detection) in sediment samples from central Oahu streams, and this was attributed to the degradation of these compounds in soils. The concentrations of organochlorine pesticides in sediment samples from Helemano and Waikele Streams (Green and others, 1977) that mainly drained agricultural areas in central Oahu were much lower than concentrations in sediment samples from canals in the urban area of Honolulu (Bevenue and others, 1972a).

Thirty-three pesticides (23 herbicides, 9 insecticides, and 1 fungicide) were detected in surface-water samples collected from Waikele Stream (USGS station 16213000) during 1999 to 2001 as part of the NAWQA study. Waikele Stream drains a mixed agricultural and urban area. Pesticides that were detected in more than 20 percent of filtered samples from Waikele Stream included bromacil, atrazine, diazinon, carbaryl, imazaquin, diuron, malathion, and simazine, and other pesticides also were detected at lower frequencies. Some pesticides were more prevalent during low-flow conditions, whereas other pesticides were more prevalent during high-flow conditions. During low-flow conditions, ground-water discharge to streams is the main component of stream discharge, whereas during high-flow conditions, direct runoff is the main component of stream discharge. Atrazine was detected in about 86 percent (12 of 14) of samples collected during low-flow conditions, reflecting the input of atrazine from ground water, and in 14 percent (1 of 7) of samples collected during high-flow conditions. (The herbicide atrazine was commonly used for sugarcane cultivation in the area near the Waikele Stream sampling site.) In comparison, diazinon was detected in 100 percent (7 of 7) of samples collected during high-flow conditions, reflecting the input of diazinon from direct runoff, and in about 7 percent of samples (1 of 14) collected during low-flow conditions.

Ground Water

The chemical composition of ground water is dependent on a number of factors including rainwater and irrigation-water quality, geology, soils, vegetation, wildlife and livestock, chemical use, and others. Although information on ground-water quality in areas upgradient from urban and agricultural activities generally reflects the background ground-water quality unaffected by human activities, airborne contaminants can be transported to undeveloped areas and ultimately reach the ground-water body. Ground water may be chemically altered as a result of human activities in developed areas. Shallow unconfined aquifers are most susceptible to contamination, especially where ground-water recharge rates are high. Even deep aquifers, however, can be contaminated.

Sources of ground-water contamination that result from human activities are classified as point or nonpoint. Point sources are specific local sites from which contaminants are discharged. Common types of point sources are cesspools, disposal wells, landfills, industrial sites, and underground storage tanks. Nonpoint sources extend over broad areas and include agricultural fields treated with pesticides or fertilizers and residential areas where chemicals are used near homes and on lawns. Human activities associated with urban and agricultural areas can have a significant effect on ground-water quality.

Natural Factors

Insofar as they are unaffected by human activities, natural factors that can affect ground-water quality include rainfall, evapotranspiration, geology, soils, and ground-water mixing. The chloride concentration of rainfall on Oahu generally is a few to a few tens of milligrams per liter. Because a fraction of the rainfall is returned to the atmosphere by evapotranspiration, the salinity of the water that recharges the ground-water system generally is greater than the salinity of the rainfall. Furthermore, salt spray from the ocean that is deposited on the land surface can contribute to increased salinity of the recharge water. Thus, the chloride concentration of fresh ground water may be higher than the concentration in rainfall. Areas of high rainfall and low evapotranspiration rates generally have lower concentrations of dissolved constituents than areas of low rainfall and high evapotranspiration rates (Visher and Mink, 1964). Mixing of fresh ground water with underlying saltwater derived from the ocean also affects the chloride concentration of the ground water.

Carbon dioxide may be present in the plant root zone as a result of plant respiration. Infiltrating water may combine with the carbon dioxide to produce carbonic acid (H_2CO_3), which is a source of carbonate and bicarbonate ions in ground water (Swain, 1973).

The soils and volcanic rocks through which water moves in the unsaturated zone, as well as the volcanic rocks through which ground water flows, affect the quality of ground water. For example, much of the silica in ground water is derived from the volcanic rocks. As ground water flows from the dike-impounded system to downgradient freshwater-lens systems, the silica concentration of the ground water increases because of dissolution of the volcanic rocks along the flow path. Visher and Mink (1964) estimated that about 54 mg/L of dissolved constituents (silica, calcium, magnesium, sodium, potassium, phosphate, and fluoride) in ground water in the freshwater-lens system in Koolau Basalt is derived from the volcanic rocks. Geothermal activity also may affect the quantity and types of dissolved constituents in ground water (Swain, 1973).

Dissolution of limestone deposits provides a source of carbon dioxide, calcium, and bicarbonate in coastal ground water where these rocks are present (Visher and Mink, 1964). Ground water in noncalcareous sedimentary deposits may contain higher concentrations of calcium and magnesium relative to ground water in other rocks because of cation exchange processes (Swain, 1973).

Urban-Related Factors

Urbanization can affect ground-water quality in a variety of ways: ground-water withdrawals can lead to saltwater intrusion; pesticides and fertilizers applied at the surface may leach to underlying ground water; chemical spills, pipeline leaks, leaky underground storage tanks, and illegal disposal of wastes can be sources of urban-related contaminants to ground water; injection of wastewater into the ground-water system or waste disposal to cesspools can lead to increased nutrient concentrations and pathogens; and landfills can be a source of metals and other urban-related contaminants.

Long-term ground-water withdrawals in an island environment cause a decline in water levels, a reduction of ground-water discharge to streams, springs, and the ocean, and saltwater intrusion (the landward and upward movement of the brackish-water transition zone).

One of the most significant ground-water quality issues on Oahu is the possibility of saltwater intrusion caused by ground-water withdrawals. Saltwater intrusion may occur in freshwater-lens systems and in dike-impounded systems in coastal areas where brackish water underlies freshwater. The degree of saltwater intrusion depends on several factors, which include the hydraulic properties of the rocks, recharge rate, pumping rate, and well location. Wells completed in the freshwater lens near the coast are particularly likely to induce brackish-water or saltwater movement into the well as pumping continues. Many wells on Oahu that are drilled too deeply or that withdraw ground water at high rates have been affected by saltwater intrusion, resulting in increased sodium and chloride concentrations in pumped water.

Ground-water withdrawal ultimately reduces the amount of discharge to springs, streams, or the ocean by the amount that is withdrawn. Reduction of springflow and streamflow is a concern for several reasons, including loss of habitat for native aquatic species and reduced water supply for agricultural diversions, aesthetics, and recreational use.

During 1971, chlordane, DDT, dieldrin, and lindane, which were commonly used in urban areas, were detected in wells, tunnels, and springs on Oahu at levels below 0.005 µg/L, although the sites where these organochlorine pesticides were detected were not specified (Bevenue and others, 1972a). During the 1990's, dieldrin and chlordane were detected in Oahu ground-water samples from wells near older urban areas that existed prior to the 1970's. Dieldrin concentrations in ground-water samples were less than 0.1 µg/L, and chlordane concentrations were less than 0.3 µg/L (State of Hawaii, 1999a).

As of 2002, there were more than 1,000 leaky underground storage tanks reported on Oahu (State of Hawaii, 2002b). The leaky underground storage tanks mainly are owned by the military and private businesses on the island, and are a potential source of petroleum-related contaminants and solvents in ground water. Petroleum-related compounds including benzene, ethylbenzene, toluene, xylene, naphthalene, and others have been detected, at concentrations generally less than a few micrograms per liter, in ground-water samples near military fuel-storage facilities within the Pearl Harbor ground-water area of central Oahu (The Environmental Company, Inc., 2001). Because EDB was used in a tetraethyl lead mixture added to aviation fuels (Lau, 1985), documented and undocumented leaks of aviation fuel from military pipelines in central Oahu (Engineering-Science, 1984) may be a source of EDB contamination of ground water in the area above Pearl Harbor, although other sources of EDB exist.

Other organic compounds including trichloroethylene (TCE), tetrachloroethylene (PCE), and carbon tetrachloride have been detected in ground-water samples on Oahu (Giambelluca and others, 1987; State of Hawaii, 1999a), although the source of these contaminants generally is uncertain. TCE is used as a dry-cleaning agent, metal degreaser, solvent, refrigerant, heat-exchange liquid, fumigant, and anesthetic (Verschueren, 2001), and has been detected in numerous wells in central Oahu since 1985 (Giambelluca and others, 1987; State of Hawaii, 1999a). PCE is used as a dry-cleaning agent, metal degreaser, and solvent, and in the manufacturing of paint removers, printing inks, trichloroacetic acid, and fluorocarbons (Verschueren, 2001), and has been detected in wells in central Oahu and the Honolulu area (Giambelluca and others, 1987; State of Hawaii, 1999a; State of Hawaii, 2001b). Some of the ground water that is contaminated with TCE and PCE and that is withdrawn from the Schofield ground-water area for military use is treated with an aeration system. Carbon tetrachloride, which is used as a solvent, extractant, metal degreaser, and fumigant, and is also used in dry-cleaning operations and the manufacturing of refrigerants, aerosols, propellants, and chlorofluoromethanes (Verschueren, 2001), also has been detected in wells in the Schofield ground-water area (Giambelluca and others, 1987; State of Hawaii, 1999a).

Waste disposal through injection wells or cesspools could potentially lead to increased nutrient concentrations, bacteria, viruses, or pharmaceutical products in ground water, although no significant ground-water-quality problems associated with injection wells or cesspools on Oahu were known to have been documented. Illegal disposal of industrial wastes in cesspools represent a potential source of industry-related contaminants in ground water (State of Hawaii, 2000a).

Agriculture-Related Factors

Withdrawal of ground water for agricultural purposes can affect water quality in the same way as withdrawal for other purposes. Agricultural activities also can affect ground-water quality through the use of pesticides, fertilizers, and irrigation water. Significant quantities of pesticides have been used on pineapple and sugarcane fields on Oahu. Some of the pesticides used for agricultural purposes have been detected in ground-water samples from wells on Oahu.

From 1982 to 1983, nine drinking-water wells in the Pearl Harbor ground-water area were closed because of DBCP or EDB contamination (Oki and Giambelluca, 1987). At the time of the well closures, concentrations of DBCP and EDB detected in water samples from the wells respectively were less than 0.1 and 0.2 μg/L. DBCP and EDB were soil fumigants that commonly were used by pineapple growers in central Oahu. In central Oahu, DBCP and EDB were detected in water samples from numerous other wells in addition to the closed wells. The contaminated well sites are restricted to areas that are hydraulically downgradient from areas of pineapple cultivation (fig. 25) (Oki and Giambelluca, 1987).

The compound 1,2,3-trichloropropane (TCP) also has been detected in ground-water samples from wells that are hydraulically downgradient from areas of pineapple cultivation (Oki and Giambelluca, 1987). TCP is a paint and varnish remover, solvent, and degreasing agent (Agency for Toxic Substances and Disease Registry, 2002), and also was an impurity of the soil fumigant DD (Carter, 1954) that was commonly used for pineapple cultivation in central Oahu. DBCP, EDB, and TCP also have been detected in soil and saprolite samples from borings in central Oahu pineapple fields, in some cases at depths exceeding 100 ft (State of Hawaii, 1983; Peterson and others, 1985).

The compound 1,2-dichloropropane (DCP) also has been detected in ground-water samples from wells in central Oahu, although the TCP contamination appears to be more widespread. DCP was a component of soil fumigants including DD, and also was found in paint strippers, varnishes, and furniture-finish removers (Agency for Toxic Substances and Disease Registry, 2002). The Honolulu Board of Water Supply currently is treating the water contaminated with DBCP, EDB, and TCP using granular activated carbon filters.

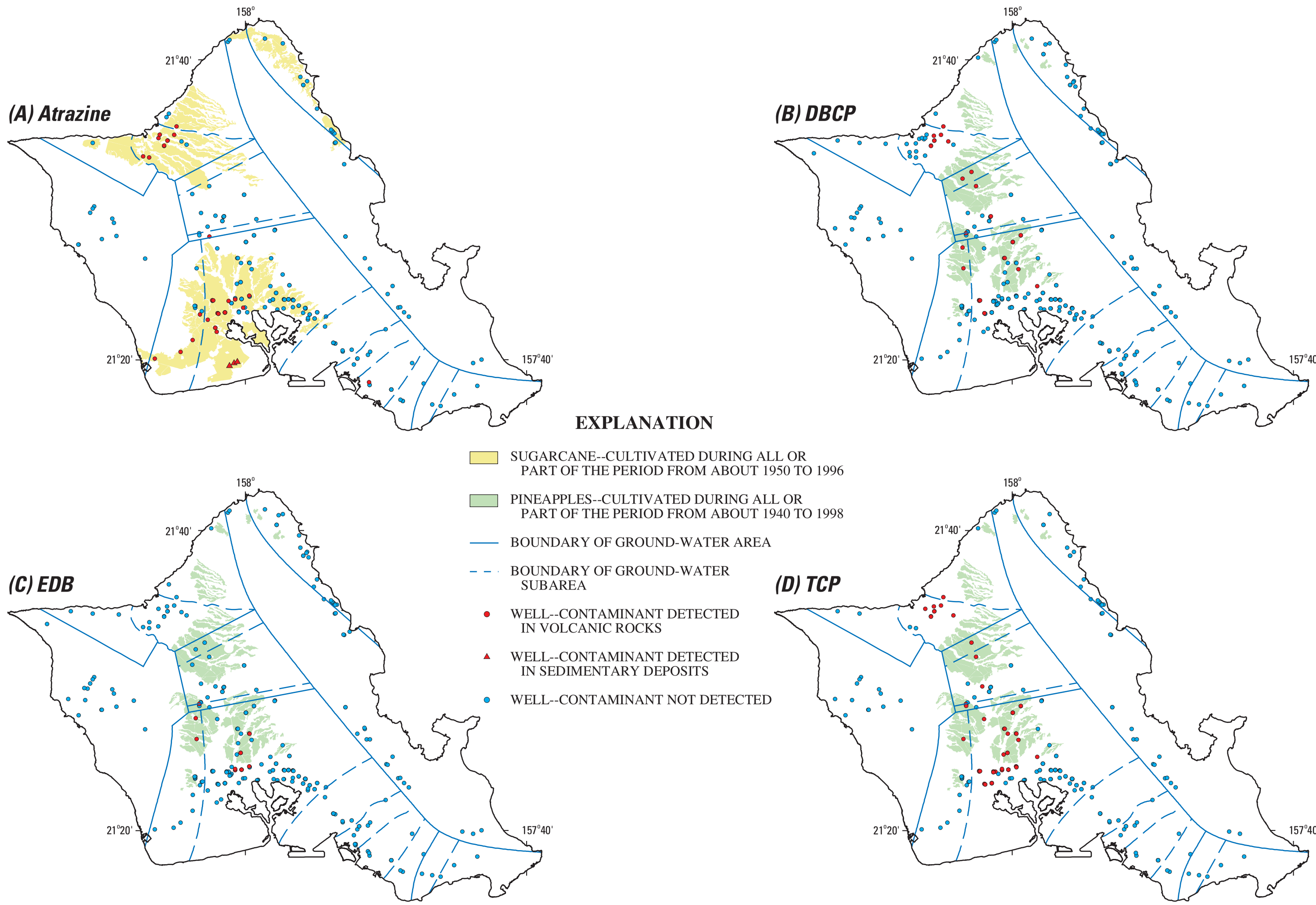


Figure 25. Areas used for sugarcane and pineapple cultivation, island of Oahu, Hawaii, and well sites sampled for (***A***) atrazine or its degradation products, (***B***) 1,2-dibromo-3-chloropropane (DBCP), (***C***) 1,2-dibromoethane (EDB), and (***D***) 1,2,3-trichloropropane (TCP). Water-quality information from Giambelluca and others (1987), Ciba-Geigy Corporation (1996), State of Hawaii (1999a), U.S. Geological Survey (2002a), U.S. Geological Survey water-quality data base and unpublished data, and unpublished data from 1995 to 2002 from State of Hawaii, Department of Health, Safe Drinking Water Branch.

Atrazine was a herbicide most commonly used for sugarcane in central Oahu, although it also was used for pineapples and diversified agriculture; government agencies also have used atrazine (table 4). Atrazine and its degradation products mainly have been detected in water samples from wells hydraulically downgradient from areas where sugarcane was cultivated (fig. 25) (Giambelluca and others, 1987; Ciba-Geigy Corporation, 1996; State of Hawaii, 1999a).

Applications of pesticides on agricultural fields represent potential nonpoint sources of ground-water contamination, whereas spills of agricultural chemicals represent potential point sources of contamination. In 1977, about 500 gallons of EDB was spilled within 100 ft of a private water-supply well (Del Monte Corp. Kunia well 2703-01) in central Oahu. Although EDB was not detected (0.5 µg/L limit of detection) in water samples collected from the well about a week after the spill, the incident focused attention in Hawaii on the potential for ground-water contamination by pesticides. By 1980, several laboratories confirmed the presence of DBCP and EDB in water from the Del Monte Corp. Kunia well, with DBCP concentrations ranging from 0.5 to 11 µg/L and EDB concentrations ranging from 92 to 300 µg/L (Giambelluca and others, 1987). The Del Monte Corp. Kunia well is not downgradient from any pineapple fields that received regular applications of DBCP, although DBCP was used experimentally. An investigation related to the contamination (Mink, 1981) revealed that EDB and DBCP spills occurred during mixing and transfer operations at a nearby chemical storage area, and these spills may have contributed to the contamination.

Irrigation water used for agricultural crops may affect ground-water quality directly (because of the quality of the irrigation water) and indirectly (because increased recharge may result in greater leaching of applied agricultural chemicals). From the 1960's to the early 1980's, the chloride concentration of water from the U.S. Navy Waiawa shaft (located near the confluence of Waiawa and Waimano Streams), a primary drinking water source in southern Oahu for the military, rose from less than 100 mg/L to over 250 mg/L. The increase in chloride concentrations was attributed to irrigation of nearby sugarcane fields with brackish ground water (Eyre, 1983). Within about 2 years after the brackish-water irrigation was stopped in the early 1980's, the chloride concentration of water from the Waiawa shaft decreased to about 100 mg/L. The chloride concentration from Waiawa shaft is currently less than 50 mg/L (fig. 26).

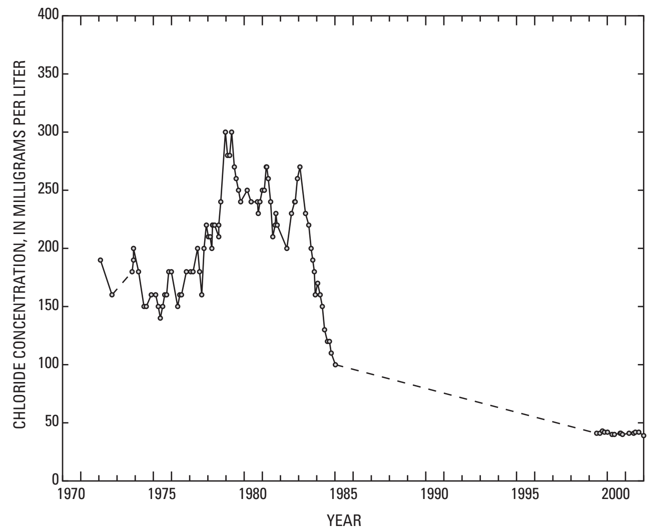


Figure 26. Chloride concentration of water from the Waiawa shaft (well 2558-10), 1972–2001, Oahu, Hawaii. Data points connected with a dashed line if separated by more than a year.

Increased nitrate concentrations in ground water may be an indicator of fertilizers used for agricultural purposes (Visher and Mink, 1964; Tenorio and others, 1969; Tenorio and others, 1970). In general, phosphorus fertilizers have not significantly affected ground-water quality on Oahu because phosphate is retained in soils by goethite and, to a lesser extent, other iron and aluminum oxides and hydroxides (Parfitt and others, 1975; McLaughlin and others, 1981; Barron and others, 1988).

A large amount of nitrate may be adsorbed on positively charged iron and aluminum oxide particles in the subsoil and saprolite beneath pineapple and sugarcane cultivation areas of central Oahu (Uehara, 1996; Deenik, 1997). Although pineapple and sugarcane plants are acid-tolerant, many diversified crops may require amendments such as lime to reduce soil acidity. The nitrate-adsorption capacity of the subsoil and saprolite is reduced as pH increases and, thus, nitrate mobility in the subsurface may be enhanced as large-scale agriculture is replaced with diversified agriculture (Deenik, 1997).

Visher and Mink (1964) indicated that nitrate (as nitrogen) concentrations of about 1 mg/L reflect ground water that is unaffected by fertilizer inputs. Nitrate concentrations of ground-water samples from wells downgradient from agricultural areas on Oahu have exceeded 8 mg/L (Visher and Mink, 1964; Tenorio and others, 1969; Tenorio and others, 1970). In parts of the Pearl Harbor ground-water area, nitrate concentrations of ground-water samples have increased from less than 2.3 mg/L during the 1950's and 1960's to as much as 7.6 mg/L in 1992 to 1994 (Ling, 1996).

The Wahiawa Reservoir (Lake Wilson) (fig. 1) in the Schofield area was completed in 1906 to provide water for irrigation of sugarcane fields in northern Oahu. Since 1928, wastewater effluent from a county-operated secondary treatment facility (Wahiawa wastewater treatment plant) has been discharged into the reservoir (Young and others, 1975). A second, smaller county-operated treatment facility (Whitmore Village wastewater treatment plant) also discharged effluent into the reservoir between 1969 and 1994 (City and County of Honolulu, 2001). Treated wastewater also is used to irrigate golf courses in some coastal areas of Oahu. No known incidents of ground-water contamination by bacteria or viruses have been attributed to the reuse of wastewater on Oahu, which generally is consistent with studies on bacteria and virus removal by Oahu soils (Tanimoto and others, 1968; Hori and others, 1970; Lau and others, 1975; Chang, 1976; Lau and others, 1980; Fujioka and Lau, 1985; Lau and others, 1989). Fujioka and Yoneyama, (2001) indicated that fecal indicator bacteria (fecal coliform, *E. coli*, and fecal streptococcus) were present in 2 of 2 water samples from springs and tunnels in remote areas away from human habitation, and in 2 of 79 water samples from wells on Oahu. The indicator bacteria exist naturally in the soil environment and, thus, the presence of indicator bacteria in ground water may not be related to fecal matter (Fujioka and Yoneyama, 2001).

Livestock operations are another potential source of nutrients and pathogens that could affect ground-water quality, although no documented cases of ground-water contamination by livestock operations on Oahu are known.

Aquatic Biota

Natural factors, including the presence of waterfalls that may preclude upstream migration of some native fishes, streamflow, and habitat availability, may affect the abundance and distribution of native freshwater macrofauna. Both urban and agricultural practices have affected streamflow, habitat availability, and water quality of Oahu's streams. The fragmentation of stream habitat through degradation of instream and riparian areas, along with a proliferation of nonnative fish and crustaceans, has resulted in a paucity of native freshwater macrofauna on Oahu (Kinzie, 1990).

By 1978 at least 58 percent of the estimated 366 perennial streams in Hawaii had some type of streamflow alteration (Parrish and others, 1978). Streamflow can be reduced by withdrawal of ground water from wells, shafts, and tunnels, or by direct diversion of surface water. Results can vary from a slight reduction in streamflow to completely drying sections of the stream. This reduction in flow can be especially significant for amphidromous species that must migrate between the stream and the ocean to complete their life cycle. Larvae may be entrained (captured) by diversion weirs and ditch systems as they wash downstream, and both downstream dispersal and upstream migration are impeded by dry stream reaches. Human modifications of island streams have typically been most severe at lower elevations, which also may have the greatest effects on the migrations of seaward-moving larvae and returning juveniles (Maciolek, 1977; Ford and Kinzie, 1982; Kinzie, 1990; Resh and others, 1992; Pringle, 1997).

A study comparing two streams on the island of Molokai, one diverted (Waikolu) and one with a natural flow regime (Pelekunu), showed a significant reduction in habitat availability in the diverted stream (Brasher, 1997). Overall, there was a reduction in channel width, depth, and water velocity in the diverted stream. There also was less variability in the range of depth and flow characteristics. This reduction in habitat availability was reflected in lower densities of native fish and higher overlap among species in the diverted stream (Brasher, 1997). In addition, few fish were found in sampled areas above the water diversions, presumably because of the difficulty in traversing the periodically dry reach just downstream of the diversions (Brasher, 1996; 1997).

A study conducted on the island of Maui at sites above and below a major water diversion on Iao Stream showed that a reduction in streamflow had significant negative effects on species diversity and densities of macroinvertebrate communities (McIntosh and others, 2002). In addition, several invertebrate species (*Atyoida bisulcata*, *Procanace* sp., and Amphipoda) that utilize fast-flowing torrential habitats were absent below the diversion structures (McIntosh and others, 2002). This was likely caused by the lack of preferred riffle habitat at the sampled site below the diversion.

An 11-month restoration of natural flows over a Kauai hydropower weir that was destroyed by a major hurricane also demonstrates the relation among stream diversion, species composition, and community structure (Kido, 1996). The undiverted stream segment was characterized by fewer species in higher densities, typical of native stream community structure in Hawaii. Species composition also varied, with the algae *Cladophora* sp. and *Nostoc* sp. dominant in the unaltered habitat while *Spirogyra* sp. was dominant in the diverted reach (Kido, 1996). Following flow restoration, invertebrate and algal biomass below the diversion reached nondiverted levels in just 8 weeks. Once flow diversion resumed, densities also declined rapidly. Interestingly, overall community structure did not recover as rapidly, and differences between the altered and unaltered sites in numbers and abundances of individual species, dominant species, and colonization rates, remained throughout the study period (Kido, 1996).

The native stream fauna in Hawaii are adapted to the torrential flows and episodic floods that occur in Hawaiian stream systems. Episodic floods following periods of significant rainfall appear to play an important role (1) as cues for reproduction and for return of larvae to streams and (2) in regulating aquatic communities (Kinzie and Ford, 1982; Brasher, 1997; McIntosh and others, 2002). Stream diversions can reduce the frequency and magnitude of floods, potentially disrupting community structure (McIntosh and others, 2002). The introduced species present in Hawaii typically are not adapted to withstand, and may be unable to survive, such torrential flows (Brown and others, 1999).

In addition to the direct effects on aquatic biota caused by water diversions, sublethal or indirect effects, including competition, predation, behavioral changes, changes in life-history characteristics, and alterations of food chains, potentially can result from streamflow alterations (Brasher, 1997, McIntosh and others, 2002).

Artificially straightened reaches with concrete-lined, flat-bottomed channels, or revetted (reinforced) banks are common in urban areas of Oahu. Such stream modifications are commonly accompanied by removal of riparian vegetative cover, and a reduction in substrate heterogeneity (removal of large boulders). The end result is a wide, shallow, unshaded, and generally homogenous stream reach; a stark contrast to the steep, heavily vegetated, boulder-strewn reaches typical of the more pristine streams in forested areas of Hawaii.

In areas where streams have been channelized, the implications of channel modification for the native stream organisms are substantial. In areas where the stream channel has been straightened, velocities generally will be increased. If the channel bottom also has been lined with concrete, the resulting flow commonly will be a thin, uniform sheet of water. In combination with a lack of riparian vegetation, and consequently no shading, daytime water temperatures may rapidly rise (fig. 27). Channelized urban streams on Oahu have higher daily mean and maximum temperatures, and greater fluctuations in temperature within a day than streams in more pristine, forested areas of Hawaii. In addition, intense daytime light and heat may promote excessive algal growth in streams in urban areas, which in turn may result in strong fluctuations in pH and dissolved oxygen within a day (Norton and others, 1978).

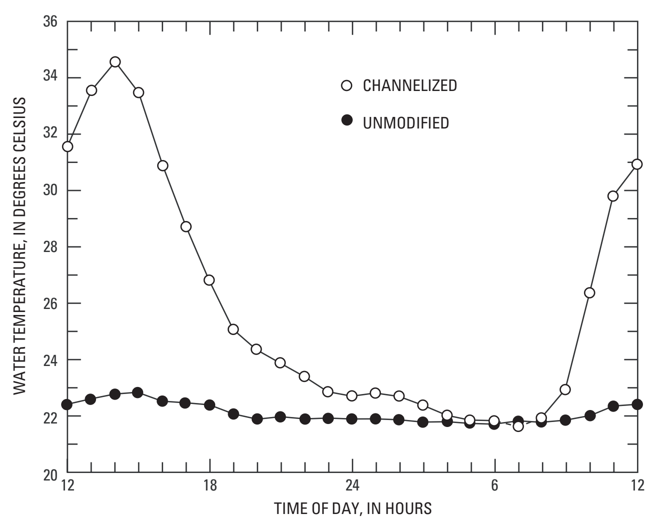


Figure 27. Changes in water temperature over a 24-hour period in an unmodified section and a channelized section of Palolo Stream, Oahu, Hawaii (modified from Hathaway, 1978).

A variety of pesticides, nutrients, and metals are associated with urban and agricultural land uses. These constituents may be related to land applications of pesticides and fertilizers, automobiles, or industrial uses of chemicals. The contaminants mainly are transported through soil erosion and surface runoff to nearby streams. Contaminants that are dissolved in the water or adsorbed to sediment can affect the fish and benthic invertebrates that live in the streams.

Although production or use of many organochlorine compounds, including pesticides and PCBs, has been banned in the United States for more than 25 years, some organochlorine compounds continue to be detected in streambed sediment and fish tissue across the Nation. Organochlorine compounds can occur at levels that exceed criteria for the protection of stream-dwelling fish and invertebrates, and the wildlife that consume them. Other, semi-volatile, organic compounds such as phenols, phthalates, and PAHs continue to have widespread usage today. Because these compounds are persistent, tend to accumulate in sediment and biota, and are potentially harmful, they are a management concern.

The presence and persistence of organic compounds has been well documented in the temperate continental United States (Schmitt and others, 1990; Nowell and others, 1999; Van Metre, 2000; Wong and others, 2000). Less is known of their fate in tropical island systems, but previous studies in Hawaii have shown concentrations of certain compounds to be among the highest in the Nation (Bevenue and others, 1972a; Tanita and others, 1976; Schmitt and others, 1981, 1985, 1990, 1999; Hunter and others, 1995; Brasher and Anthony, 2000).

From the 1950's through the mid-1980's, large amounts of organochlorine pesticides were applied in urban Oahu to control termites and mosquitoes. Over 60 million dollars has been spent annually to prevent and control infestations of the Formosan subterranean termite (*Coptotermes formosanus* Shiraki) and to repair the damage they cause to buildings (Yates and Tamashiro, 1990). The organochlorine pesticides chlordane, aldrin/dieldrin, and heptachlor commonly were used for termite control. In 1977, 125,600 pounds of chlordane, 24,000 pounds of heptachlor, and 9,000 pounds of aldrin were used for pest control in Hawaii (Takahashi, 1982). In recent years, less persistent organophosphate and pyrethrin chemicals have had a prominent role in control of subterranean termites. Also, various termite-bait systems are widely used.

The aerial spraying of the insecticide DDT for mosquito control to prevent the transmission of human diseases such as malaria was widespread in urban areas (Rinella and others, 1993). DDT also was viewed as highly beneficial to crop production and used liberally to control many agricultural insect pests prior to its ban in 1972.

As part of the National Pesticide Monitoring Program, later called the National Contaminant Biomonitoring Program (NCBP), the U.S. Fish and Wildlife Service (USFWS) periodically analyzed selected organochlorine compounds and trace elements in fish from more than 100 sites around the Nation between 1970 and 1986, including two streams, Waikele and Manoa, on Oahu (Schmitt and others, 1981, 1985, 1990, 1999). Following a trend that has been observed across the country (Schmitt, 1990; Nowell and others, 1999; Wong and others, 2000), concentrations of organochlorine compounds are generally decreasing in Oahu streams.

Concentrations of total DDT in fish from Oahu streams were among the highest in the Nation in NCBP samples from 1980–81 (Schmitt, 1985). Oahu streams also had the highest proportion of DDT to DDD and DDE in the Nation (Schmitt, 1985). Because DDT is metabolized to DDD and DDE, proportionately high concentrations of DDT suggest recent or continuing inputs of DDT to the aquatic ecosystem. Nationally, mean concentrations of total DDT in fish declined significantly over the period 1976–86 (Schmitt and others, 1999), and this also was true for Oahu.

The highest concentrations of dieldrin (the degradate of aldrin) and chlordane measured in fish across the Nation occurred in Oahu streams every year that they were measured as part of the NCBP (Schmitt and others, 1999). Aldrin and various chlordane compounds, used extensively in Hawaii for termite control, were phased out of use or banned in the mid-1980's. In general, chlordane concentrations in fish did not change nationally between 1978–79 and 1980–81, but did drop significantly in Oahu streams, although Oahu streams continued to have the highest concentrations in the Nation (Schmitt and others, 1985). Concentrations of dieldrin and chlordane in oysters near stream mouths draining urban Kaneohe in windward Oahu in 1991 were found to exceed USEPA screening levels to protect human health (Hunter and others, 1995).

Land use has a strong effect on the spatial distribution and abundance of many trace elements in soils and stream sediments, and in Hawaii, concentrations of metals are commonly highest in urban areas (De Carlo and Anthony, 2002). Mining and coal-burning operations have been major sources of metal release to the aquatic environment in continental areas; however, it is likely that only a small contribution from these sources reaches Hawaii through atmospheric transport (De Carlo and Spencer, 1995, 1997).

In fish samples collected for the NCBP, concentrations of lead at urban Manoa stream were the highest in the Nation (Schmitt, 1999). Nationally, the mean concentration of lead in fish declined significantly and steadily from 1976 through 1986 (Schmitt, 1999). This also was true for Manoa Stream, although concentrations there remained the highest in the Nation throughout the sample period. Much of the anthropogenic lead input to the atmosphere between 1940 and 1975 consisted of lead-alkyl fuel additives. In Hawaii during 1971, nearly 450 metric tons of lead was released to the environment due to the use of leaded gasoline (De Carlo and Spencer, 1997). Concentrations of lead in sediment at the Ala Wai Canal (fig. 1) were correlated to the use of leaded fuel, peaking in the mid-1970's, and decreasing more recently (De Carlo and Spencer, 1995, 1997).

Oysters from the mouth of Kaneohe Stream and at a nearby marina had high tissue concentrations of lead, copper, chromium, and zinc (Hunter and others, 1995). Likewise, sediment samples from the urban Ala Wai Canal showed elevated levels of copper, cadmium, and zinc, in addition to lead (De Carlo and Spencer, 1995, 1997). Copper concentrations measured in fish at Waikele Stream (a watershed with both urban and agricultural influence) as part of the NCBP in 1984 and 1986 were among the highest in the Nation (Schmitt, 1999). In Hawaii, copper has been used in residential areas (wood-preservative chemicals) and at small boat marinas (Hunter and others, 1995).

Arsenic in Hawaiian stream sediments has been found to be associated with agriculture, including small-scale nurseries (De Carlo and Anthony, 2002). Other metals, such as nickel, may be related to mineralogy in Hawaii, rather than human activities (De Carlo and Spencer, 1997).

Organic compounds, trace elements, and metals can enter the aquatic environment from a variety of sources including the atmosphere, industrial and municipal effluents, and agricultural and urban nonpoint-source runoff. For example, organochlorine pesticides, PCBs, and semivolatile organic compounds typically have low solubility and commonly are transported through soil erosion and surface runoff. They are commonly associated with bottom sediments, which can be transferred to benthic algae and invertebrates. These organisms are then eaten by fish and birds, which can result in higher concentrations through aquatic and terrestrial food chains.

Many contaminants have been linked to detrimental effects on stream biota, ranging from acute exposure (leading directly to mortality) to chronic and indirect effects. Many organochlorine pesticides are known animal carcinogens and are potential human carcinogens (Nowell and others, 1999). The adverse effects of DDT on reproduction in birds has been well documented (Faber and Hickey, 1973), and other organochlorine pesticides have been linked to a range of sublethal effects including biochemical and physiological changes, behavioral changes, suppressed immune-system responses, reduced fecundity, morphological deformations, and endocrine disruption (Murty, 1986; Madhun and Freed, 1990). Endocrine disruption in particular has been the focus of an increasing number of scientific investigations in recent years (Goodbred and others, 1996; Kavlock and others, 1996; Colborn and Thayer, 2000).

SUMMARY AND CONCLUSIONS

The island of Oahu is the third largest island of the State of Hawaii, and is formed by the eroded remnants of the Waianae and Koolau shield volcanoes. The landscape of Oahu ranges from a broad coastal plain to steep interior mountains. Topography of the island affects climate, which is characterized by mild temperatures and cool and persistent northeasterly trade winds. Rainfall is greatest in the mountainous interior parts of the island, and lowest near southwestern coastal areas.

The volcanoes that formed the island of Oahu have undergone significant modification by processes such as subsidence, weathering, erosion, and deposition. Subsidence has drowned coastal areas and subaerially formed valleys. Chemical weathering has led to decomposition of volcanic rocks and leaching of soluble decomposition products of the rocks. Streams have further modified the volcanoes by incising deep valleys and transporting material to coastal areas. Deposits of marine and terrestrial sediments have formed a coastal plain of varying width around the island.

The structure and form of the two volcanoes in conjunction with processes that have modified the original surfaces of the volcanoes control the hydrologic setting. The rift zones of the volcanoes contain dikes that tend to impede the flow of ground water, leading to high ground-water levels in the dike-impounded ground-water system. In the windward (northeastern) part of the island, ground-water levels in the dike-impounded system may reach the land surface in stream valleys, resulting in ground-water discharge to streams. Where dikes are not present, the volcanic rocks are highly permeable and a lens of freshwater overlies a brackish-water transition zone separating the freshwater from saltwater. Ground water discharges to subaerial coastal springs and streams where the water table in the freshwater-lens system intersects the land surface. Low-permeability terrestrial and marine sediments have been deposited on the volcanic rocks in most coastal areas, and discharge of ground water from the volcanic rocks to the ocean is impeded by this sedimentary caprock.

The Waianae and Koolau Ranges have been deeply dissected by numerous streams with main courses that generally have followed the consequent drainage pattern on the original volcanoes. Streams originate in the mountainous interiors of the Waianae and Koolau Ranges and terminate at the coast. Some of these streams flow perennially throughout their entire course, others flow perennially over parts of their course, and the remaining streams flow during only parts of the year throughout their entire course. Streams commonly flow perennially in the interior parts of the island where they gain water from the dike-impounded ground-water body and where rainfall is persistent, or near the coast where the water table is higher than the steam level. In general, drainage basins on Oahu are small and streams are flashy. However, streamflow characteristics are highly variable, both spatially and temporally.

Hawaiian streams have relatively few native species compared to continental streams. Widespread diverse orders of insects are absent from the native biota, and there are only five native fish, two native shrimp, and a few native snails. The native fish and crustaceans of Hawaii's freshwater systems are all amphidromous, a type of diadromy in which adult lives are spent in streams, and larval periods as marine or estuarine zooplankton.

During the 20th century, land-use patterns on Oahu reflected increases in population and decreases in large-scale agricultural operations over time. The last two remaining sugarcane plantations on Oahu closed in the mid-1990's, and much of the land that once was used for sugarcane now is used for diversified agriculture or developed for urban uses. Although two large pineapple plantations continue to operate in central Oahu, some of the land previously used for pineapple cultivation has been developed for urban uses.

Both natural and human-related factors control surface- and ground-water quality and the distribution and abundance of aquatic biota on Oahu. Natural factors that may affect water quality include geology, soils, vegetation, rainfall, ocean-water quality, and air quality. Human-related factors associated with urban and agricultural land uses also may affect water quality. Ground-water withdrawals may cause saltwater intrusion. Numerous pesticides that were used in agricultural or urban areas have been detected in surface and ground water on Oahu. Petroleum-related compounds including benzene, ethylbenzene, toluene, xylene, and naphthalene, have been detected, at concentrations generally less than a few micrograms per liter, in ground-water samples near military fuel-storage facilities in central Oahu. Other organic compounds including trichloroethylene, tetrachloroethylene, and carbon tetrachloride have been detected in ground-water samples on Oahu, although the source of these contaminants generally is uncertain.

Organic compounds, including acetone, chloroform, benzene, toluene, styrene, and xylene, that are commonly associated with urban-related activities were detected in water samples from Manoa Stream generally at concentrations below 1 microgram per liter. Toluene also was detected in stormwater runoff samples from residential and commercial areas on Oahu, and phenols were detected in storm runoff from residential, commercial, and industrial areas on Oahu. Various polycyclic aromatic hydrocarbons have been detected in storm runoff from a freeway on Oahu.

Increased nitrate concentrations in ground water in southern Oahu over time may be associated with agricultural use of fertilizers. Runoff from agricultural and urban areas also may contribute nitrogen and phosphorus to streams. Elevated concentrations of lead above natural background concentrations in sediments mainly have been attributed to automotive emissions on Oahu.

Natural factors, including the presence of waterfalls that may preclude upstream migration of some native fishes, streamflow, and habitat availability, may affect the abundance and distribution of native freshwater macrofauna on Oahu. Urban and agricultural practices have affected Oahu’s streams. The resulting fragmentation of stream habitat through degradation of instream and riparian areas, along with a proliferation of nonnative fish and crustaceans, has resulted in a paucity of native freshwater macrofauna on Oahu. The amphidromous life cycle of the native freshwater fish and crustaceans makes them particularly vulnerable to even localized habitat alterations that may prevent downstream dispersal of larvae or upstream migration of postlarvae, and can influence the distribution of these species throughout the watershed.

A variety of pesticides, nutrients, and metals are associated with urban and agricultural land uses. These constituents may be related to land applications of pesticides and fertilizers, automobiles, or industrial uses of chemicals. The contaminants mainly are transported through soil erosion and surface runoff to nearby streams. Contaminants that are dissolved in the water or adsorbed to sediment can affect the fish and benthic invertebrates that live in the streams.

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Table 4. Pesticides used for selected times during 1964–2000, island of Oahu, Hawaii. In some cases, information for Oahu only was not available and, thus, statewide information was used. Other pesticides may have been used on Oahu, although published information was not available to include other pesticides in this table.

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Pesticide	Chemical class	Earliest year[a]	Year introduced or registered	Sugarcane[b]	Pineapples[c]	Other row crops and orchards[c,d]	Horticulture[b]	Live-stock, grazing, pasture, and non-crop[b]	Golf courses[c]	Residential areas[c]	Pest-control operators[c]	Government[c,e]	Restricted-use pesticides purchased in 2000[b]
				Source of information									
Insecticides													
2-Butoxy-2-thiocyanodiethyl ether	nc	1932	--	--	--	--	--	--	--	2,3	--	--	--
2-Hydroxy-N-octyl sulfide	nc	--	1962[f]	--	--	--	--	--	--	2,3	--	--	--
2,3,4,5-bis(Butylene) tetrahydro-2-furaldehyde	nc	--	--	--	--	--	--	--	--	2,3	--	--	--
Abamectin	antibiotic	1981	--	--	--	--	--	--	--	--	--	--	9
Acephate	organophosphorus	1969	1973[f]	--	--	--	3	--	--	3,6	--	3,5	--
Aldicarb	carbamate	1954	1965	--	--	4	3,4	--	--	--	1,3	--	--
Aldrin	organochlorine	1959	--	--	--	--	--	--	--	--	2	3	--
Allethrin	pyrethroid	1828	--	--	--	--	--	--	--	2,3,6	--	3	--
Ammonium fluorosilicate	nc	--	--	--	--	--	--	--	--	--	3	--	--
Arsenic trioxide	arsenical	--	--	--	--	--	--	--	--	2	--	--	--
Azinphosmethyl (guthion)	organophosphorus	--	1959[f]	--	--	1,2,3	--	--	--	--	--	3	9
B. Thuringiensis	bacterial	1938	1961[f]	--	--	--	--	--	--	6	--	3	--
Bendiocarb	carbamate	1971	1980[f]	--	--	--	--	--	7	6	3,6	3,5	9
β-Naphthol	nc	--	--	--	--	--	--	--	--	2,3	--	--	--
Biphenthrin	pyrethroid	1984	--	--	--	--	--	--	--	--	--	--	9
Boric acid	inorganic	--	1948[f]	--	--	--	--	--	--	2,6	--	--	--
Butoxypolypropylene glycol	nc	--	--	--	--	--	--	--	--	2	--	3	--
Carbaryl	carbamate	--	1956	8	--	1,2,3	3	--	1,7	2,6	1,3,6	1,3,5	--
Carbarylphen	nc	--	--	--	--	--	--	--	--	3	--	--	--
Carbofuran	carbamate	--	--	--	--	3,4		4	--	--	--	--	--
Chlordane	organochlorine	1945	--	--	1,2	1	4	--	1	2	1,2,3,6	1,2,3,5	--
Chlordecone (kepone)	organochlorine	--	1958	--	--	--	--	--	--	2,3	1,2	1	--
Chlorobenzilate	organochlorine	1952	--	--	--	1,2	--	--	--	--	--	--	--
Chlorpyrifos	organophosphorus	1965	1965	3,8	--	--	--	--	7	2,3,6	2,3,6	1,2,3,5	--
Copper acetoarsenate (Paris Green)	arsenical	1867	--	--	--	--	--	--	--	--	2,3	1,3	--
Copper acetoarsenite	arsenical	--	--	--	--	--	--	--	--	--	--	5	--
Copper hydroxide (kocide)	nc	--	1968	--	--	1	--	--	--	--	--	--	--
Coumaphos	organophosphorus	--	1958[f]	--	--	--	--	1,3	--	--	--	--	--
Crotoxyphos	organophosphorus	1962	1963	--	--	--	--	3	--	--	--	3	--
Crufomate	organophosphorus	--	--	--	--	--	--	3	--	--	--	--	--

Table 4. Pesticides used for selected times during 1964–2000, island of Oahu, Hawaii. In some cases, information for Oahu only was not available and, thus, statewide information was used. Other pesticides may have been used on Oahu, although published information was not available to include other pesticides in this table.--Continued

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				Source of information									
Cyanobenzeneacetate	nc	--	--	8	--	--	--	--	--	--	--	--	--
Cypermethrin	pyrethroid	1975	--	--	--	--	--	--	--	--	6	--	--
DDT	organochlorine	1939	--	--	1,2	1	--	1	1	--	1	1	--
DDVP (dichlorvos; vapona)	organophosphorus	1951	--	--	--	--	--	3	--	2,3,6	1,2,3,6	1,2,3,5	--
Demeton	organophosphorus	--	--	--	--	--	--	--	--	--	--	2	--
Diazinon	organophosphorus	1952	1952	1,8	1,2,3,5	1,2,3	3	--	1,3	2,3,6	1,2,3,6	1,2,3,5	9
Dichlorodifluoromethane (freon-12)	nc	1931	--	--	--	--	--	--	--	--	3	--	--
Dicofol (kelthane)	organochlorine	--	1955	--	--	1,2,3	--	--	--	2,3,6	--	3,5	--
Dieldrin	organochlorine	1948	--	--	--	1	--	--	1	2	1,2	1,3	--
Dienochlor	organochlorine	--	1960	--	--	--	--	--	--	--	--	3,5	--
Diflubenzuron	urea derivative	1972	1976[f]	--	--	--	--	--	--	--	--	3	--
Dimethoate (cygon)	organophosphorus	--	1956	--	--	1,2,3	--	--	--	3	--	1,3,5	--
Dioxathion (delnav)	organophosphorus	--	1954	--	--	--	--	3	--	2	1,3,6	--	--
Disulfoton	organophosphorus	--	1961[f]	--	5	3	--	--	--	3	--	2,3	9
Emamectin benzoate	antibiotic	--	--	--	--	--	--	--	--	--	--	--	9
Endosulfan (thiodan)	organochlorine	1956	1956	--	--	1,2,3,4	4	--	1	--	--	1,3,5	9
Endrin	organochlorine	--	1951	--	--	1	--	--	--	--	--	--	--
Essential oil	oil	--	--	--	--	--	--	--	--	3	--	--	--
Ethion	organophosphorus	--	1955	--	--	3	--	--	--	--	--	5	--
Ethoprop	organophosphorus	--	1967[f]	--	--	--	--	--	7	--	--	--	--
Fenbutatin-oxide	organotin	--	1974[f]	--	--	--	3	--	--	--	--	--	9
Fenchlorphos (korlan, ronnel)	organophosphorus	--	1954	1	--	--	--	--	--	2	1,3	1,2,3	--
Fenpropathrin	pyrethroid	1981	--	--	--	--	--	--	--	--	--	--	9
Fensulfothion	organophosphorus	--	1957	--	--	--	3	--	--	--	--	--	--
Fenthion (baytex)	organophosphorus	--	1965[f]	1	--	--	--	--	--	--	--	1,2,3	--
Fenvalerate	pyrethroid	--	--	--	--	--	--	--	--	--	--	5	9
Fluvalinate	pyrethroid	--	--	--	--	--	--	--	7	--	--	--	--
Griseofluvin	antibiotic	1939	--	--	--	--	--	--	--	--	--	5	--
Heptachlor	organochlorine	1951	1952[f]	8	1,2,3,5	1	--	--	--	--	2,3,6	1,5	--
Hexachlorophene	nc	1939	--	--	--	--	--	--	--	2	--	--	--
Hydramethylnon (amdro)	nc	--	1980[f]	8	--	--	--	--	7	--	--	--	--
Hydroprene	insect growth regulator	1973	--	--	--	--	--	--	--	6	6	--	--
Isofenphos	organophosphorus	1974	1980[f]	--	--	--	--	--	--	--	6	--	--

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				Source of information									
λ–Cyhalothrin	pyrethroid	1984	1985	--	--	--	--	--	--	--	--	--	9
Lead arsenate	arsenical	1892	--	--	--	--	--	--	--	2	--	--	--
Lindane	organochlorine	1940's	--	--	1,2,3,5	--	3	1	--	2	1	1,3	9
Malathion	organophosphorus	--	1950	1	1,2,3,5	1,2,3	--	1,3	--	2,3,6	3	1,2,3,5	--
Metaldehyde	nc	1936	--	--	--	--	--	--	--	2,3,6	--	2,3,5	--
Methamidophos (monitor)	organophosphorus	--	1969	--	--	2	--	--	--	--	--	--	--
Methiocarb	carbamate	--	1958	--	--	--	--	--	--	2,3,6	--	--	9
Methomyl	carbamate	--	1968[f]	--	2,5	2,3,4	3,4	--	--	--	--	3,5	9
Methoprene	insect growth regulator	--	1975[f]	8	--	--	--	--	--	6	6	3	--
Methoxychlor	organochlorine	1944	--	--	--	1	--	1	--	2,3,6	--	--	--
Methyl parathion	organophosphorus	--	1949	--	--	--	--	--	--	--	--	--	9
Methylene chloride	nc	--	--	--	--	--	--	--	--	--	3	--	--
Mevinphos (phosdrin)	organophosphorus	1953	1953	--	--	1,2,3,4	--	--	--	--	--	3	--
Mirex	organochlorine	1954	--	3	2,3,5	--	--	--	--	--	--	--	--
N-Octyl bicycloheptene dicarboximide	nc	1949	--	--	--	--	--	--	--	2,3,6	3	3	--
Naled (dibrom)	organophosphorus	--	1956	--	--	1,2,3	--	1	--	2,3,6	--	3,5	--
Nicotine	nc	--	--	--	--	--	--	--	--	3,6	--	2	--
Oxamyl (vydate)	carbamate	--	1974[f]	--	5	4	3,4	4	--	--	--	5	9
Oxydemeton-methyl	organophosphorus	1956	1960	--	--	--	--	--	--	2,3	--	3	9
Paradichlorobenzene	nc	1915	--	--	--	--	--	--	--	2,3	--	--	--
Parathion	organophosphorus	1944	1947	--	1	1,2,3	--	--	--	--	--	--	--
Pennyroyal oil	oil	--	--	--	--	--	--	--	--	2,3	--	--	--
Pentachlorophenol	organochlorine	1936	--	--	--	--	--	--	--	2,3	1,2,3	3	--
Permethrin	pyrethroid	1973	--	--	--	--	--	--	--	6	6	--	9
Petroleum oil (e.g. volck)	oil	1922	--	--	--	--	--	--	--	3,6	--	2,3	--
Phenothrin (chloromethiuron)	pyrethroid	1975	--	--	--	--	--	--	--	6	--	--	--
Phosphamidon	organophosphorus	1956	1956	--	--	1	--	--	--	--	--	--	--
Pine oil	oil	--	--	--	--	--	--	--	--	3	--	--	--
Piperonyl bis(2-butoxyethoxy) ethyl acetate	nc	--	--	--	--	--	--	--	--	2	--	--	--
Piperonyl butoxide	nc	1947	--	--	--	--	--	--	--	2,3,6	1,2,3	1,2,3	--
Piprotal	nc	--	--	--	--	--	--	--	--	2	--	--	--
Propetamphos (safrotin)	organophosphorus	--	1980[f]	--	--	--	--	--	--	--	6	--	--

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				Source of information									
Propoxur	carbamate	--	1963[f]	--	--	--	--	--	--	2,3,6	1,2,3,6	1,2,3,5	--
Pyrethrins (pyrethrum)	botanical insecticide	1820	--	--	--	--	--	--	--	2,3,6	1,2,3	1,2,3,5	--
Pyrethroids	pyrethroid	--	--	--	--	--	--	--	--	--	--	--	9
Resmethrin	pyrethroid	1967	--	--	--	--	--	--	--	2,3,6	3	--	--
Rotenone	botanical insecticide	1848	--	--	--	--	--	1	--	2,3,6	--	--	--
Silica gel	inorganic	--	--	--	--	--	--	--	--	2	2,3	--	--
Silikil	inorganic	--	--	--	--	--	--	--	--	--	1	--	--
Sulfur	inorganic	--	--	--	--	2,3	--	--	--	2,3,6	--	5	--
Sulfoxide	nc	--	--	--	--	--	--	--	--	2,3	--	--	--
TDE (dichlorodiphenyl dichloroethane)	organochlorine	--	--	--	--	--	--	--	--	2	--	--	--
Temephos (abate)	organophosphorus	--	1965	1	--	--	--	--	--	--	--	1,2,3,5	--
Tetrachloroethylene		--	--	--	--	--	--	--	--	--	3	--	--
Tetrachlorvinphos (stirofos; gardona)	organophosphorus	1966	1966[f]	--	--	2	--	3	--	3	--	3	--
Tetraethyl pyrophosphate (TEPP)	organophosphorus	1939	--	--	--	1	--	--	--	--	--	--	--
Tetramethrin	pyrethroid	--	1965	--	--	--	--	--	--	2,3,6	--	--	--
Toxaphene	organochlorine	1947	1948	--	--	3	--	1	--	--	--	--	--
Trichlorfon (dylox)	organophosphorus	--	1955[f]	--	--	--	--	--	1	2	--	1,3	--
Trichloroethylene	nc	--	--	--	--	--	--	--	--	--	3	--	--
Trichloromonofluoromethane	nc	--	--	--	--	--	--	--	--	--	3	--	--
Xylene	nc	--	--	--	--	--	--	--	--	2	--	--	9
Fungicides													
Anilazine (dyrene)	nc	1955	1955	--	--	2	--	--	1,7	--	--	1	--
Benomyl	benzimidazole	--	1968	3,8	2,3,5	2,3,4	3,4	4	7	3,6	--	3,5	--
Calcium hypochlorite	nc	1798	--	--	--	--	--	--	--	--	--	3,5	--
Calcium polysulfides	sulfur	1800's	--	--	--	--	--	--	--	3	--	--	--
Cadmium carbonate	nc	--	--	--	--	--	--	--	--	--	--	1	--
Captafol	dicarboximide	--	1961	--	2,3	2,4	4	--	--	--	--	--	--
Captan	dicarboximide	--	1951[f]	--	1,2,3,5	1,2,3	3	--	--	2,3,6	--	1,3,5	--
Chlorothalonil (bravo; daconil)	aromatic	--	1966[f]	--	--	2,3	--	--	1,7	6	--	1,5	--
Copper hydroxide	inorganic	--	1968	--	--	3	--	--	7	--	--	5	--

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				Source of information									
Copper oleate	nc	--	--	--	--	--	--	--	--	2,3	--	--	--
Copper sulfate	inorganic	1807	--	--	--	1,2,3	--	--	--	3	--	3,5	--
Dichloran	nc	--	1959	--	--	2	--	--	--	--	--	--	--
Dichlorophen	nc	1946	--	--	--	--	--	--	--	2,3	--	--	--
Dicofol	organochlorine	--	1955	--	5	--	--	--	--	--	--	3	--
Dinocap (karathane)	dinitrophenol	--	1946	--	--	2	3	--	--	--	--	3	--
Etanzol	nc	--	--	--	--	--	3	--	--	--	--	--	--
Etridiazole (terrazol, korban)	thiazole	1962	1962[f]	--	--	--	3	--	--	--	--	5	--
Fenaminosulf	nc	--	1955	--	1	--	--	--	--	--	--	--	--
Ferric sulfate	nc	--	--	--	--	--	--	--	--	3	--	--	--
Folpet (phaltan)	dicarboximide		1948[f]	--	--	2	3	--	--	2,3,6	--	--	--
Fosetyl-al	nc	1977	1983[f]	--	--	--	--	--	7	--	--	--	--
Iprodione	dicarboximide	--	1979[f]	--	--	--	--	--	7	--	--	--	--
Mancozeb (dithane M-45)	dithiocarbamate	--	1961	--	1	1,2,3	3	--	1,3,7	3,6	1	1,2,3,5	--
Maneb (dithane M-22)	dithiocarbamate	--	1950	--	--	1,2,3	--	--	--	3	--	5	--
Metalaxyl	substituted dimethyl aniline	1977	1979[f]	--	--	--	--	--	7	--	--	--	--
Methyl mercury salts	mercury	--	--	1	--	--	--	--	--	--	--	--	--
Oxythioquinox	dithiocarbonate	1960	1968[f]	--	--	--	--	--	--	--	--	3	--
Parinol	nc	--	--	--	--	--	--	--	--	3	--	--	--
Pentachloronitrobenzene (PCNB)	organochlorine	1930's	--	--	--	3	--	--	7	--	--	1,3,5	--
Phenylmercuric acetate (PMA)	mercury	1914	--	1	--	--	--	--	--	--	--	1	--
Propiconazole	conazole	1979	--	8	--	--	--	--	--	--	--	--	--
Sodium bisulfate	nc	--	--	8	--	--	--	--	--	--	--	--	--
Sodium o-phenylphenate	nc	--	--	--	3	--	--	--	--	--	--	--	--
Sulfur	inorganic	--	--	--	--	1,2,3	--	--	--	--	--	3	--
TC-90 copper	nc	--	--	--	--	1	--	--	--	--	--	--	--
Thiophanate, methyl	carbamate	--	1971	8	--	--	3	--	--	--	--	--	--
Thiram	dithiocarbamate	1931	--	--	--	--	3	--	--	2,3,6	--	1,5	--
Town and turf	nc	--	--	--	--	--	--	--	1	--	--	1	--
Tribasic copper	copper	--	--	--	--	1	--	--	--	--	--	--	--
Triforine	nc	1970	--	--	--	--	--	--	--	6	--	--	--
Zineb	dithiocarbamate	1943	--	--	--	1,2,3	--	--	--	3	--	--	--

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				Source of information									
Herbicides and growth regulators													
2,4-D	phenoxy	1942	--	1,2,3,8	--	1,4	3,4	1,3	1,7	2,3,6	--	1,2,3,5	9
2-Naphthyl acetic acid (BNA)	nc	--	--	--	1	--	--	--	--	--	--	--	--
2,4,5-T	phenoxy	1944	1944	1,2	--	--	--	1,3	1	--	--	1,2,3	--
Acifluorfen	diphenyl ether	--	--	--	--	--	--	--	--	6	--	--	--
Alachlor	amide	--	1969[f]	--	--	3	--	--	--	--	--	3,5	9
α-Naphthalene acetic acid	auxins	--	--	--	2,3	--	--	--	--	--	--	--	--
Ametryn	triazine	1960	1964	1,2,3,8	1,2,3,5	3,4	--	--	--	--	--	1,3,5	--
Amitrole	triazole	--	1948[f]	1,2	--	1	3	1	--	2,3,6	--	1,2,3,5	--
Ammonium sulfamate (AMS)	inorganic	1942	--	1	--	--	--	--	--	3,6	--	1,2,3,5	--
Asulam	carbamate	1965	1975[f]	3,8	--	--	--	--	--	--	--	--	--
Atrazine	triazine	1957	1958	1,2,3,8	1,2,3,5	1,2,3,4	3,4	1,3,4	--	--	--	1,2,3,5	9
Benefin (benfluralin; balan)	dinitroaniline	--	1963	--	--	1,2,3	3	--	3	--	--	3,5	--
Bensulide	organophosphorus	--	1964[f]	--	--	--	--	--	7	--	--	--	--
BOH	nc	--	--	--	1	--	--	--	--	--	--	--	--
Boric acid (borates)	inorganic	--	1948[f]	--	--	--	3	3	--	3	--	1,2,3,5	--
Bromacil	uracil	--	1961[f]	1,2	1,2,3,5	--	--	--	--	--	--	1,2,3,5	--
Bromoxynil	nitrile	1963	1965[f]	--	--	--	3	--	--	--	--	--	--
Butylate	thiocarbamate	--	1967[f]	--	--	3	--	--	--	--	--	3,5	--
Cacodylic acid (dimethylarsonic acid)	organic arsenical	--	1958	--	--	--	3	--	1	2,3	--	1,2,3,5	--
CDEC (vegadex)	thiocarbamate	--	1954	--	--	1,2,3	--	--	--	--	--	2,3	--
Chlorates	inorganic	1900's	--	1	--	1	3	3	--	3	--	1,2,3,5	--
Chlorazine	triazine	--	--	--	--	--	--	--	--	--	--	3	--
Chlorflurenol, methyl ester	nc	--	1965	--	5	--	--	--	--	--	--	--	--
CIPC (chlorpropham)	carbamate	--	1951	--	--	1	--	--	--	--	--	--	--
Cyanazine	triazine	--	--	--	--	--	--	--	--	--	--	--	9
Dacthal (DCPA)	chlorinated benzoic acid	--	1958[f]	--	--	1,2,3	--	--	--	2,3,6	--	1,2,3,5	--
Dalapon	halogenated aliphatic	--	1953	1,2,3,8	1,2,3,5	1,2,4	4	1	1	3	--	1,2,3,5	--
Dicamba	nc	--	--	8	--	--	3	3	1,7	2,3,6	--	1,2,3,5	9
Dichlobenil	nitrile	1960	1964[f]	--	--	--	--	--	--	3	--	--	9
Dinoseb	dinitrophenol	1945	--	--	--	--	--	--	--	--	--	3	--
Diphenamid	amide	--	--	--	--	1,3	--	--	--	--	--	3	--

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				Source of information									
Diquat	Bipyridylium	--	1957	1,2,3,8	--	--	--	--	--	--	--	1,2,3,5	9
Diuron	urea	1951	1954	1,2,3,8	1,2,3,5	1,2,4	4	1	--	3	--	1,2,3,5	--
EPTC	thiocarbamate	--	1958[f]	--	--	3	3	--	--	2,3	--	--	--
Erbon	phenoxy	--	1955	--	--	--	--	--	--	2,3	--	--	--
Ethephon	nc	1965	1973[f]	8	2,3,5	--	--	--	--	--	--	--	--
Ethylene	nc	--	1971[f]	--	1,2,3,5	--	--	--	--	--	--	--	--
Fluazifop-butyl	phenoxy	--	--	--	--	--	--	--	--	6	--	--	--
Gibberellic acid	gibberellins	1926	1947[f]	3	--	--	--	--	--	--	--	--	--
Glyphosate	organophosphorus	--	1971	3,8	5	3,4	3,4	3,4	3,7	3,6	--	3,5	--
Glyphosine	nc	--	1969	3	--	--	--	--	--	--	--	--	--
Hexazinone	triazine	--	1975[f]	3,8	5	--	--	--	--	--	--	--	--
Imazaquin	imidazolinone	--	--	--	--	--	--	--	7	--	--	--	--
Linuron	urea	1962	1966[f]	--	--	--	--	--	1	--	--	1,3,5	--
Maleic hydrazide	nc	1895	1952[f]	--	--	--	--	--	--	--	--	1	--
Mecoprop (MCPP)	phenoxy	1953	--	--	--	--	3	--	7	2,3,6	--	3	9
Methanearsonate (CAMA, DSMA, MAMA, MSMA)	organic arsenical	1956	--	1,2	--	--	3	--	1,3,7	2,3,6	--	1,2,3,5	9
Metribuzin	triazine	1968	--	3,8	--	--	--	--	7	--	--	5	--
Monuron	urea	--	1951	2	1	--	--	--	--	--	--	1,3	--
Nitrofen (TOK)	diphenyl ether	--	1961	--	--	1,2,3	--	--	--	--	--	--	--
Oryzalin	dinitroaniline	1969	1974[f]	--	--	--	--	--	7	--	--	--	--
Oxadiazon	nc	1963	--	--	--	--	--	--	7	--	--	5	--
Oxyfluorfen	diphenyl ether	1975	--	8	--	--	--	--	--	6	--	--	--
Paraquat	quaternary nitrogen	1958	1958	1,2,3,8	--	1,2,3,4	3,4	1,3,4	1	2,3	--	1,2,3,5	--
Paraquat dichloride	quaternary nitrogen	1958	1964[f]	--	--	--	--	--	--	--	--	--	9
Pendimethalin (prowl)	dinitroaniline	1972	1974[f]	--	--	--	--	--	7	--	--	--	--
Pentachlorophenol (PCP)	nc	1936	--	1	1	1	--	1,3	--	--	--	1,2	--
Petroleum oil	oil	1922	--	--	--	2	--	3	--	--	--	--	--
Picloram	aromatic acid	1960's	1964[f]	1,2,3,8	--	--	--	3	--	--	--	1,2,3,5	--
PNBP	nc	--	--	--	--	--	--	--	--	--	--	1	--
Prometon	triazine	--	1959	--	--	--	--	--	--	3,6	--	1,2,5	--
Pronamide	amide	1969	1972[f]	--	--	3	3	--	7	--	--	--	9
Silvex (fenoprop)	phenoxy	1945	1953	1,2,3,8	--	--	--	3	--	2,3	--	2,3	--
Simazine	triazine	1956	1956	8	1	2,4	3,4	3	1,7	--	1	1,2,3,5	--

Table 4. Pesticides used for selected times during 1964–2000, island of Oahu, Hawaii. In some cases, information for Oahu only was not available and, thus, statewide information was used. Other pesticides may have been used on Oahu, although published information was not available to include other pesticides in this table.--Continued

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Pesticide	Chemical class	Earliest year[a]	Year introduced or registered	Sugarcane[b]	Pineapples[c]	Other row crops and orchards[c,d]	Horticulture[b]	Live-stock, grazing, pasture, and non-crop[b]	Golf courses[c]	Residential areas[c]	Pest-control operators[c]	Government[c,e]	Restricted-use pesticides purchased in 2000[b]
				Source of information									
SNA	nc	--	--	--	1	--	--	--	--	--	--	--	--
Sodium arsenate	arsenical	--	--	--	--	--	--	--	--	--	--	1,2	--
Sodium arsenite	arsenical	1890	--	--	--	--	--	3	--	2	--	--	--
Sulfometuron methyl	urea	--	--	8	--	--	--	--	--	--	--	--	--
Terbacil	uracil	1962	1966[f]	2,3,8	--	--	--	--	--	--	--	--	--
Trichloroacetic acid (TCA and STCA)	halogenated aliphatic	1947	--	1,2,8	--	--	--	1	--	--	--	1	--
triclopyr	pyridine	--	1979[f]	--	--	--	--	--	--	6	--	--	--
trifluralin (treflan)	dinitroaniline	1960	1963[f]	8	--	1,2,3	3	3	--	2,3	--	1,3,5	--
Fumigants													
1,2-Dibromo-3-chloropropane (DBCP)	chlorinated hydrocarbon	1955	1955	--	1,2,3,5	3,4	--	--	--	--	--	--	--
Aluminum phosphide	inorganic	--	1958[f]	--	--	--	--	--	--	--	3	--	9
Chloropicrin	nc	1908	--	--	5	--	3	--	--	--	2,3	--	9
Ethylene dibromide	chlorinated hydrocarbon	1925	1946	--	1,2,3,5	--	--	--	--	--	--	2,3	--
Methyl bromide	nc	1932	--	--	1	4	3,4	--	1	2	2,3	1,2,3,5	9
1,3-Dichloropropene (telone)	chlorinated hydrocarbon	--	1954[f]	--	1,2,3,5	4	3	--	--	--	--	3	9
mixture of 1,3-Dichloropropene; 1,2-Dichloropropane; and 2,3-Dichloropropene (DD)	chlorinated hydrocarbon	1943	--	--	1,2,3	--	--	--	--	--	--	3	--
Sodium methyl-dithiocarbamate (metham)	nc	1951	1954	--	--	--	3	--	--	--	--	2,3	--
Sulfuryl fluoride (vikane)	inorganic	1957	1957	--	--	--	--	--	--	--	2,3	3,5	9
Avicides													
4-Aminopyridine	pyridine	--	--	--	--	--	--	--	--	--	--	--	9
Molluscicides													
Calcium arsenate	arsenical	1906	--	--	--	--	--	--	--	2	--	1	--
Methiocarb (mesurol)	carbamate	--	1958	--	--	--	--	--	--	2,6	--	--	--
Metaldehyde	nc	1936	--	--	--	--	--	--	--	--	--	1	--

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Pesticide	Chemical class	Earliest year[a]	Year introduced or registered	Sugarcane[b]	Pineapples[c]	Other row crops and orchards[c,d]	Horticulture[b]	Live-stock, grazing, pasture, and non-crop[b]	Golf courses[c]	Residential areas[c]	Pest-control operators[c]	Government[c,e]	Restricted-use pesticides purchased in 2000[b]
				Source of information									
Nematicides													
Ethoprop	organophosphorus	1967	--	--	2	--	--	--	--	--	--	--	--
Fenamiphos	organophosphorus	1969	--	--	2,3,5	4	3,4	--	--	--	--	--	9
Fensulfothion	organophosphorus	--	1957	--	2	--	--	--	--	--	--	--	--
Rodenticides													
Anticoagulant	nc	--	--	--	--	--	--	--	--	--	--	3	--
Coumafuryl	coumarin	1951	--	8	--	--	--	--	--	--	--	--	--
Diphacinone (diphacin)	indandione	1958	--	8	--	--	--	--	--	--	3	1	--
Pindone	indandione	1942	--	8	--	--	--	--	--	--	--	--	--
Pyriminil	nc	--	--	--	--	--	--	--	--	--	3	--	--
Sodium fluoroacetate (compound 1080)	nc	1946	--	1	--	--	--	--	--	--	--	--	--
Thallium sulfate	inorganic	--	--	1	--	--	--	--	--	--	--	--	--
Warfarin	coumarin	1944	1952[f]	--	--	--	--	--	--	--	--	1	--
Zinc phosphide	inorganic	--	1947[f]	3,8	--	--	--	--	--	--	3	--	--
Miscellaneous													
Allyl isocyanate	nc	--	--	--	--	--	--	--	--	3	--	--	--
Bone oil	oil	--	--	--	--	--	--	--	--	3	--	--	--
Deet	dialkylamide	--	1957[f]	--	--	--	--	--	--	2,3	--	--	--
Di-*N*-propyl isocinchomerate	nc	--	--	--	--	--	--	--	--	3	--	--	--
Methyl nonyl ketone	aliphatic ketone	--	1966[f]	--	--	--	--	--	--	3	--	--	--
Sassafras oil	oil	--	--	--	--	--	--	--	--	3	--	--	--

[a]year discovered, first described, first used, or patented (Spencer, 1982; Thomson, 1986; Tomlin, 1994)
[b]only statewide information available
[c]information for Oahu used if available, but statewide information also may be included
[d]includes vegetable and fruit crops, but not pineapple and sugarcane
[e]includes federal, state, and county government use of pesticides for various purposes
[f]registration dates from U.S. Environmental Protection Agency, Reregistration Eligibility Decision (RED) documents

GLOSSARY

Aa– Lava flows characterized by a rough, jagged, spinose, clinkery surface, a relatively dense central core, and a rubbly layer beneath the core.

Alkalic basalt– One of two general varieties of basaltic rock containing relatively low concentrations of silica and high concentrations of the alkalies sodium and potassium. In Hawaii, alkalic basalts and their derivatives commonly form the late-stage volcanics of shield volcanoes.

Alluvium– Unconsolidated material composed of clay, sand, or gravel and deposited by water.

Amphidromy– A type of diadromy that is not related to spawning but occurs regularly at some other stage of the life-cycle. For freshwater species in Hawaii this includes a marine larval life-stage.

Anthropogenic– A condition that is the result of, or is influenced by, human activity.

Aquifer– A water-bearing layer of soil, sand, gravel, or rock that will yield usable quantities of water to a well. In Hawaii, the most important aquifers are volcanic-rock aquifers.

Background concentration– A concentration of a substance in a particular environment that is indicative of minimal influence by human (anthropogenic) sources.

Base flow– Sustained, low flow in a stream; ground-water discharge is the source of base flow in most places.

Bed sediment– The material that temporarily is stationary in the bottom of a stream or other watercourse.

Benthic– Refers to plants or animals that live on the bottom of lakes, streams, or oceans.

Brackish water– As used in this report, brackish water refers to water with a dissolved chloride concentration greater than that of freshwater (250 milligrams per liter) and less than that of saltwater (19,500 milligrams per liter).

Caldera– A large basin-shaped volcanic depression. In Hawaii, calderas commonly occupy the summits of younger volcanoes and are bounded by steep cliffs.

Caprock– In Hawaii, the term caprock refers to a confining unit that exists near the coast. Caprock may be composed of any or all of the following rock types: sedimentary deposits, reef limestones, weathered basalt, or massive lava flows.

Cesspool– A pit or excavation in the ground designed to receive untreated wastewater, retain solid matter, and permit liquid to seep through its bottom or sides.

Chemical weathering– The set of chemical processes by which original rock minerals are decomposed or altered to form new minerals.

Climate– The sum total of the meteorological elements that characterize the average and extreme conditions of the atmosphere over a long period of time at any one place or region of the Earth's surface.

Clinker– The rough, jagged lava commonly associated with the surface of an aa flow.

Concentration– The amount or mass of a substance present in a given volume or mass of sample. Usually expressed as micrograms per liter (water sample) or micrograms per kilogram (sediment or tissue sample).

Confined aquifer (artesian aquifer)– An aquifer that is completely filled with water under pressure and that is overlain by material that restricts the movement of water.

Confining unit– A geologic unit formed by low-permeability material stratigraphically adjacent to one or more aquifers.

Contamination– Degradation of water quality compared to original or natural conditions due to human activity.

DDT– Dichloro-diphenyl-trichloroethane. An organochlorine insecticide no longer registered for use in the United States.

Diadromy– A life-history type involving migration between salt and fresh waters.

Dike– A tabular body of igneous rock that cuts across the structure of adjacent rock and that is created by intrusion of magma. In Hawaii, dikes are commonly thin, near-vertical sheets of massive, low-permeability volcanic rock.

Dike complex– The central part of a rift zone where dikes may number as many as 1,000 per mile of horizontal distance and compose 10 percent or more of the total rock volume.

Dike-impounded ground water– Ground water that flows through dikes, over dikes, or within compartments formed by dikes.

Dike-impounded system– A ground-water system consisting of fresh, dike-impounded ground water, and where it exists, underlying brackish water and saltwater. Dike-impounded systems are found in the rift zones and caldera of a volcano where low-permeability dikes have intruded other rocks.

Dissolved constituent– Operationally defined as a constituent that passes through a 0.45-micrometer filter.

Diversion– A turning aside or alteration of the natural course of a flow of water, normally considered physically to leave the natural channel.

Drainage basin– The portion of the surface of the Earth that contributes water to a stream through overland runoff, including tributaries and impoundments.

Drinking-water standard or guideline– A threshold concentration in a public drinking-water supply, designed to protect human health. Standards are U.S. Environmental Protection Agency regulations that specify maximum contamination levels (MCLs) for public water systems required to protect the public welfare; guidelines have no regulatory status and are issued in an advisory capacity.

Ecosystem– The interacting populations of plants, animals, and microorganisms occupying an area, plus their physical environment.

Endemic– Native organisms occuring only in one restricted geographic area. A species is endemic to Hawaii if it is found only in Hawaii.

Erosion– The process whereby materials of the Earth's crust are loosened, dissolved, or worn away and simultaneously moved from one place to another.

Evapotranspiration– A collective term that includes water lost through evaporation from the soil and surface-water bodies and by plant transpiration.

Extrusive rock– Igneous rocks derived from magmas or magmatic materials poured out or ejected at the Earth's surface.

Fertilizer– Any of a large number of natural or synthetic materials, including manure and nitrogen, phosphorus, and potassium compounds, spread on or worked into soil to increase its fertility.

Flood – Any relatively high streamflow that overtops the natural or artificial banks of a stream.

Freshwater– As used in this report, freshwater refers to water with a dissolved chloride concentration less than 250 milligrams per liter.

Freshwater lens– A lens-shaped body of fresh ground water that is separated from underlying saltwater by a transition zone of brackish water.

Freshwater-lens system– A ground-water system consisting of a lens-shaped body of fresh ground water, an intermediate transition zone of brackish water, and underlying saltwater. In high-permeability settings, freshwater extends from below sea level to the water table that is generally less than a few tens of feet above sea level. In low-permeability settings, a vertically extensive freshwater-lens system may form.

Fumigant– A substance or mixture of substances that produces gas, vapor, fume, or smoke intended to destroy insects, bacteria, or rodents.

Gaging station– A particular site on a stream, canal, lake, or reservoir where systematic observations of hydrologic data are obtained.

Gaining stream– A stream or reach of a stream in which flow is being increased by inflow of ground water.

Glacioeustatic– Pertaining to simultaneous, world-wide changes in sea level in relation to glacial and interglacial periods.

Gradient– The change in the value of a quantity (such as hydraulic head or rainfall) with respect to change in a given quantity, commonly distance in a specified direction.

Ground water– In general, any water that exists beneath the land surface, but more commonly applied to water in fully saturated soils and geologic formations.

Habitat– The part of the physical environment where plants and animals live.

Head, hydraulic– The head of water at a given point is the sum of three components: (1) elevation head, which is equal to the elevation of the point above a datum; (2) pressure head, which is the height of a column of static water that can be supported by the static pressure at the point; and (3) velocity head, which is the height that the kinetic energy of the water is capable of lifting the water. Because the velocity of ground water is commonly small, velocity head in ground-water systems is commonly negligible. Head at a point in a ground-water system can be measured by the water level in a well that is open only at that point.

Herbicide– A chemical or other agent applied for the purpose of killing undesirable plants. See also Pesticide.

Hydrograph– Graph showing variation of water elevation, velocity, streamflow, or other property of water with respect to time.

Indigenous– Native organisms occurring naturally in a particular region or locality and elsewhere. A species is indigenous to Hawaii if it is native to Hawaii, and also native to at least one other region.

Infiltration– Movement of water, typically downward, into soil or porous rock.

Insecticide– A substance or mixture of substances intended to destroy or repel insects.

Instream use– Water use taking place within the stream channel for such purposes as hydroelectric power generation, navigation, water-quality improvement, fish propagation, and recreation. Sometimes called nonwithdrawal use or in-channel use.

Intermittent stream– A stream that flows only when it receives water from rainfall runoff or springs, or from some surface source such as melting snow.

Intrusive rock– Rock that solidified from magma beneath the Earth's surface.

Irrigation return flow– The part of irrigation applied to the surface that is not consumed by evapotranspiration or uptake by plants and that migrates to an aquifer or surface-water body.

Invertebrate– An animal having no backbone or spinal column.

Limestone– A sedimentary rock consisting mainly of calcium carbonate.

Load– General term that refers to a material or constituent in solution, in suspension, or in transport; usually expressed in terms of mass or volume.

Losing stream– A stream or reach of a stream that is losing water to the ground.

Mass wasting– The movement, either slow or quick, of large masses of earth material by gravity from one place to another.

Marginal dike zone– The outer part of a rift zone, beyond the dike complex, where dikes usually constitute less than 5 percent of the total rock volume.

Marine sediment– Sediment deposited in the ocean.

Micrograms per liter (μg/L)– A unit expressing the concentration of constituents in solution as weight (micrograms) of solute per unit volume (liter) of water; equivalent to one part per billion in most streamwater and ground water. One thousand micrograms per liter equals 1 mg/L.

Milligrams per liter (mg/L)– A unit expressing the concentration of chemical constituents in solution as weight (milligrams) of solute per unit volume (liter) of water; equivalent to one part per million in most streamwater and ground water. One thousand micrograms per liter equals 1 mg/L.

Mineral– A naturally occurring, solid, inorganic element or compound, with a definite composition or range of compositions.

Mouth– The place where a stream discharges to a larger stream, a lake, or the sea.

Native– Organisms that occur naturally in a particular region or locality, includes both endemic and indigenous organisms.

Nitrate– An ion consisting of nitrogen and oxygen ($NO3^-$). Nitrate is a plant nutrient and is very mobile in soils.

Nonpoint source– A pollution source that cannot be defined as originating from discrete points such as pipe discharge. Areas of fertilizer and pesticide applications, atmospheric deposition, manure, and natural inputs from plants and trees are types of nonpoint source pollution.

Nutrient– Element or compound essential for animal and plant growth. Common nutrients in fertilizer include nitrogen, phosphorus, and potassium.

Old alluvium– Terrestrial sediments, varying in size from fine-grain particles to boulders, which have been weathered and compacted into a soft coherent mass.

Organochlorine compound– Synthetic organic compounds containing chlorine. Examples include organochlorine insecticides, polychlorinated biphenyls, and some solvents containing chlorine.

Organophosphorus insecticides– Insecticides derived from phosphoric acid and are generally the most toxic of all pesticides to vertebrate animals.

Pahoehoe– Lava flows characterized by smooth, billowy, or ropy surfaces.

Pan evaporation– Evaporation measured as fluctuations of the water level, corrected for additions from precipitation, in a U.S. Weather Bureau Class A pan, which is made of unpainted, galvanized iron, supported on a low wooden frame.

Perched water– Ground water that is found on top of low-permeability rocks that impede the downward movement of water sufficiently to allow a saturated water body to develop within otherwise unsaturated rocks.

Perennial stream– A stream that normally has water in its channel at all times.

Permeability– As used in this report, permeability is a qualitative measure of the ease with which water can move through rock.

Pesticide– A chemical applied to crops, rights of way, lawns, or residences to control weeds, insects, fungi, nematodes, rodents or other "pests."

Phosphorus– A nutrient essential for growth that can play a key role in stimulating aquatic growth in lakes and streams.

Physical weathering– Physical processes leading to the disintegration of rocks.

Point source– A source at a discrete location such as a discharge pipe, drainage ditch, tunnel, well, concentrated livestock operation, or floating craft.

Precipitation– Any or all forms of water particles that fall from the atmosphere, such as rain, snow, hail, and sleet.

Pyroclastic deposit– Rocks, such as ash, cinder, and spatter, formed by explosive volcanic activity and that are deposited by transport processes related to this activity.

Recharge– Water that infiltrates the ground and reaches the saturated zone.

Relative abundance– The number of organisms of a particular kind present in a sample relative to the total number of organisms in the sample.

Rift zone– In Hawaii, a rift zone is a narrow zone of extensional fissures and eruptive vents, extending across the summit and down the flanks of volcanoes. Within a rift zone, thousands of intrusive dikes feed eruptive vents.

Riparian– Areas adjacent to rivers and streams with a high density, diversity, and productivity of plant and animal species relative to nearby uplands.

Runoff– Excess rainwater or snowmelt that is transported to streams by overland flow, tile drains, or ground water.

Saltwater– As used in this report, saltwater refers to water with a dissolved chloride concentration of about 19,500 milligrams per liter.

Saltwater intrusion– The upward and landward movement of brackish water or saltwater into parts of an aquifer that formerly contained freshwater.

Saprolite– Weathered rock retaining the structural and textural features of the parent rock

Sediment– Particles, derived from rocks or biological materials, that have been transported by a fluid or other natural process, suspended or settled in water.

Semivolatile organic compound (SVOC)– Operationally defined as a group of synthetic organic compounds that are solvent-extractable and can be determined by gas chromatography/mass spectrometry. SVOCs include phenols, phthalates, and polycyclic aromatic hydrocarbons (PAHs).

Septic tank– A watertight receptacle that receives untreated wastewater and discharges a settled, partially treated effluent.

Soil– Naturally occurring materials, made up of mineral matter, organic matter, air, and water, which form a thin layer on the surface of the Earth and provide support for plants.

Species diversity– An ecological concept that incorporates both the number of species in a particular sampling area and the evenness with which individuals are distributed among the various species.

Specific conductance– A measure of the ability of a liquid to conduct an electrical current.

Spring– A place where water flows naturally from a rock or soil upon the land or into a surface-water body.

Stage– The height of the water surface above an established datum plane, such as in a river above a predetermined point that may (or may not) be near the channel floor.

Stream reach– A continuous part of a stream between two specified points.

Strike– The course or bearing of the outcrop of a geologic bed or structure on a level surface.

Subaerial– Situated, formed, or occurring on the Earth's surface.

Submarine– Situated, formed, or occurring underwater.

Surface water– An open body of water, such as a lake, river, or stream.

Suspended (as used in tables of chemical analyses)– The amount (concentration) of undissolved material in a water-sediment mixture. It is associated with the material retained on a 0.45-micrometer filter.

Suspended sediment– Particles of rock, sand, soil, and organic detritus carried in suspension in the water column, in contrast to sediment that moves on or near the streambed.

Terrestrial sediment– Sediment deposited on land.

Tholeiitic basalt– One of two general varieties of basaltic rock containing relatively high concentrations of silica and low concentrations of the alkalies sodium and potassium. In Hawaii, tholeiitic basalts and their derivatives commonly form the bulk of shield volcanoes.

Trace element– An element found in only minor amounts in water, sediment, or rocks.

Triazine herbicide– A class of herbicides containing a symmetrical triazine ring (a nitrogen-heterocyclic ring composed of three nitrogens and three carbons in an alternating sequence). Examples include atrazine, propazine, and simazine.

Unconfined aquifer– An aquifer whose upper surface is a water table; an aquifer containing unconfined ground water.

Unconsolidated deposit– Deposit of loosely bound sediment that typically fills topographically low areas.

Upgradient– Of or pertaining to the place(s) from which ground water originated or traveled through before reaching a given point in an aquifer.

Vertically extensive freshwater-lens system– A freshwater-lens system occurring in low-permeability rocks and in which freshwater extends from below sea level to the water table that is several hundreds or even thousands of feet above sea level.

Volatile organic compounds (VOCs)– Organic chemicals that have a high vapor pressure relative to their water solubility. VOCs include components of gasoline, fuel oils, and lubricants, as well as organic solvents, fumigants, some inert ingredients in pesticides, and some by-products of chlorine disinfection.

Water table– The surface in a ground-water body at which the pressure is atmospheric. It is defined by the levels at which water stands in wells that penetrate the water body just far enough to hold standing water.

Water year– The continuous 12-month period, October 1 through September 30, in U.S. Geological Survey reports dealing with the surface-water supply. The water year is designated by the calendar year in which it ends and which includes 9 of the 12 months. Thus, the year ending September 30, 1980, is referred to as the "1980" water year.

Weathering– Processes of chemical decomposition and physical disintegration of minerals near the Earth's surface.

Withdrawal– The act or process of removing; such as removing water from a stream for irrigation or public water supply.