U.S. Department of the Interior

Hydrology and Water and Sediment Quality at James Campbell National Wildlife Refuge Near Kahuku, Island of Oahu, Hawaii

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 99-4171

Prepared in cooperation with the
U.S. FISH AND WILDLIFE SERVICE, DEPARTMENT OF THE INTERIOR

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The front and back covers show an aerial photomosaic of the Kahuku coastal plain, including the Punamano and Kii Units of the James Campbell National Wildlife Refuge. (Photography by Air Survey Hawaii. Photomosaic created by joining two digitally scanned, false-color infrared photographic prints furnished by the U.S. Fish and Wildlife Service, Haleiwa, Hawaii, dated February 2, 1991, and January 9, 1992.)

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By Charles D. Hunt, Jr., and Eric H. De Carlo

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Honolulu, Hawaii
2000

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
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Conversion Factors

Multiply	By	To obtain
acre	4,047	square meter
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
foot per mile (ft/mi)	0.1894	meter per kilometer
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
inch (in.)	2.54	centimeter
inch per year (in/yr)	2.54	centimeter per year
inch per day (in/d)	2.54	centimeter per day
mile (mi)	1.609	kilometer
gallons per minute (gal/min)	3.785	liters per minute
gallons per day (gal/d)	3.785	liters per day
million gallons (Mgal)	0.04381	cubic meters

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

$$°F=1.8°C+32$$

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

$$°C=(F–32)/1.8$$

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25°C).

Concentrations of chemical constituents and sediment in water are given either in milligrams per liter (mg/L), micrograms per liter (µg/L), or micrograms per kilogram (µg/kg).

Hydrology and Water and Sediment Quality at James Campbell National Wildlife Refuge near Kahuku, Island of Oahu, Hawaii

By Charles D. Hunt, Jr., and Eric H. De Carlo

Abstract

The James Campbell National Wildlife Refuge occupies two lowland marsh and pond complexes on the northern coastal plain of Oahu: the mostly natural ponds and wetlands of the Punamano Unit and the constructed ponds of the Kii Unit. The U.S. Fish and Wildlife Service manages the Refuge primarily to protect and enhance habitat for four endangered species of Hawaiian waterbirds. Kii Unit is fed by artesian wells and rainfall, whereas Punamano Unit is fed naturally by rainfall, runoff, and ground-water seepage. Streams drain from the uplands into lowland ditches that pass through Kii Unit on their way to the ocean. A high-capacity pump transfers water from the inner ditch terminus at Kii to the ocean outlet channel. Stormwaters also exit the inner ditch system over flood-relief swales near the outlet pump and through a culvert with a one-way valve.

A hydrologic investigation was done from November 1996 through February 1998 to identify and quantify principal inflows and outflows of water to and from the Refuge, identify hydraulic factors affecting flooding, document ground-water/surface-water interactions, determine the adequacy of the current freshwater supply, and determine water and sediment quality. These goals were accomplished by installing and operating a network of stream-gaging stations, meteorology stations, and shallow ground-water piezometers, by computing water budgets for the two Refuge units, and by sampling and analyzing water and pond-bottom sediments for major ions, trace metals, and organic compounds.

Streamflow during the study was dominated by winter stormflows, followed by a gradual recession of flow into summer 1997, as water that had been stored in alluvial fans drained to lowland ditches. Outflow at the ditch terminus in 1997 was 125 million gallons greater than measured inflow to the coastal plain, mainly reflecting gains from ground water along the ditches between outlying gages and the ditch terminus. Of the measured 1997 outflow, 98 percent was through the Kii outlet pump, with the outlet culvert valve only opening for brief periods during storms. Large volumes of stormflow overflowed the flood-relief swales unmeasured.

The largest storm of the study, in November 1996, was estimated to have a flood frequency of about 3 to 4 years. Streamflow exceeded culvert capacity and overtopped Kamehameha Highway at Kalaeokahipa Stream and Hospital ditch. Slight overbank flooding in Kii ditch resulted strictly from high discharge. Minor overbank flooding farther out on the coastal plain probably was caused mainly by the small hydraulic gradients available to convey stormflows along the lowland ditches. Stormwaters flooded Kii ponds and flowed back upstream along Punamano ditch into Punamano marsh, introducing suspended sediment and possibly other contaminants to the Refuge. Two smaller storms in January 1997 resulted in smaller flows and no overbank flooding. The Kii outlet pump ran continuously for 7 days during the November 1996 storm and for 1 to 2 days during the January 1997

storms. During all three storms, the outlet culvert valve opened and the inner ditches overtopped the flood-relief swales, allowing free outflow of water from the inner ditch.

Backwater effects hindered drainage during the January 1997 storms at Hospital ditch at Kamehameha Highway, and at Punamano ditch at Nudist Camp Road (where the backflow into Punamano marsh in November 1996 constituted an extreme backwater effect). A probable marine backwater effect was imposed at the ocean outlet ditch during the November 1996 storm through a combination of high spring tides and wave setup from large surf. Whether this backwater effect propagated upstream in the ditches to affect inland sites could not be determined conclusively. A sand plug may have built up in the ocean outlet channel before the November 1996 storm, but if so, it probably washed out prior to, or early in the storm, and was not present at the time of peak stage at inland sites. A season-long buildup of the sand plug in late 1997 was inferred from rising water levels in the outlet ditch. Seawater flows up the outlet channel or over the sand berm and into the outer ditch system on most high tides, and particularly during spring high tides.

Ponds and ditches of the Refuge and surrounding lowlands have mud- and clay-lined bottoms that form an effective confining unit and inhibit interaction with an underlying shallow limestone aquifer. At Kii Unit, pond levels are higher than adjacent ditch levels and underlying ground-water levels, establishing lateral and downward head gradients that could foster seepage losses from the ponds. Regional ground-water discharge from the Koolau aquifer to the coastal-plain sediments is mostly diffuse, but is concentrated where ridges of Koolau Basalt plunge beneath coastal-plain sediments near Punamano Unit and at the head of Hospital ditch. Kii ditch gains brackish ground water downstream of Kamehameha Highway. Wastewater disposal from the sewage treatment plant adjoining Kii Unit poses little or no threat to Refuge habitat. Disposal is at six injection wells located 0.45 mi away at Kahuku, and the wells inject into confined limestone aquifers that do not extend to Kii Unit.

The natural freshwater supply to Punamano Unit is adequate for maintaining the wildlife habitat, judging from stable pond levels and low salinities there. A monthly water budget for Punamano showed an apparent annual deficit in measurable flows in 1997, requiring unmeasured ground-water gains equalling 51 inches of water. The freshwater supply to Kii Unit is inadequate according to Refuge managers, because there is not enough water to manipulate levels adequately in the ponds during most of the year, and particularly during the driest months. This is confirmed by monthly deficits in the water budget for the Kii ponds during summer months. However, the Kii budget showed an annual surplus in measurable flows for 1997 equalling 24 inches of water. Unmeasured losses are required to explain the apparent annual surplus, such as discharge to the ditches through pond water-control structures and downward and/or lateral ground-water seepage. The apparent surplus at Kii is strictly hydrologic and is not a surplus in a management sense; it cannot be stored or used to supply the Refuge, but instead reflects losses from the system that render this amount of water unavailable for use. The budget year, 1997, was drier than normal (24 percent below long-term mean rainfall) and so the measured potential evaporation for 1997 was probably higher than the long-term mean.

Few metals or organic compounds of potential concern were detected in pond and ditch waters and in pond-bottom sediments. Detected pesticides were at trace levels or just above minimum reporting limits. Exceptions that exceeded quality guidelines for freshwater sediment were copper and zinc in sediment from Kii ponds C and D, and copper in sediment from Punamano north pond. Therefore, urban and agricultural runoff probably have contributed little in the way of harmful metals or organic compounds to the Refuge, although the potential for such contribution remains from periodic flooding of the ponds by ditch stormflows. Salinity was low throughout most Refuge waters, qualifying as fresh to slightly brackish and suitable for the environmental needs of Refuge fauna. Higher salinities have been observed in ditches during past periods of sugarcane cultivation and saltwater aquaculture, however. Resumption of saltwater aquaculture could raise ditch salinities if saltwater effluents are disposed directly into the ditches, as they were in the past.

INTRODUCTION

The James Campbell National Wildlife Refuge occupies two lowland marsh and pond complexes, the Punamano and Kii Units, on the northern coastal plain of Oahu near the town of Kahuku (fig. 1). The Refuge is managed by the U.S. Fish and Wildlife Service (USFWS) primarily to provide habitat for four native endangered species of Hawaiian waterbirds: Hawaiian coot (*Fulica alai)*, Hawaiian duck (*Anas wyvilliana*), Hawaiian stilt (*Mimantopus mexicanus knudseni*), and Hawaiian moorhen (G*allinula chloropus sandvicensis*). Management for these endangered waterbirds also provides habitat for other migratory waterbirds. To address concerns about the adequacy of existing water sources and the quality of water, and to learn more about the hydrology of a wetland in a tropical island environment, the USFWS entered into a cooperative agreement with the U.S. Geological Survey (USGS) in 1994 to conduct a hydrologic study of the Refuge. This report summarizes the results of this study.

Ponds within the Refuge are partly covered by marsh plants such as bulrush and cattails that provide nesting habitat, and the muddy pond bottoms contain invertebrates on which waterfowl feed. The Punamano Unit is a marsh and pond complex (fig. 2) that is fed by natural water sources: rainfall, runoff, at least two known springs, and perhaps by diffuse ground-water seepage. Water from the marsh drains freely into Punamano ditch and then flows east to the ditch terminus at Kii Unit. The fair-weather water level in Punamano north pond is about 2.5 ft above sea level, and the altitude of the pond bottom varies from about 0 to 2 ft above sea level. To the west lies Punahoolapa marsh (figs. 1 and 2), a former natural marsh that has been landscaped into a golf course with open-water ponds as water hazards. Marconi Road separates Punamano marsh from Punahoolapa marsh, except during extreme floods that inundate the road.

At Kii Unit (fig. 3) the former natural marsh was landscaped into an assemblage of bermed ponds that were used until 1971 for settling sugarcane wash water from nearby Kahuku Mill. In 1976, USFWS established the Kii Unit of the Refuge, supplying the ponds with water from adjacent ditches and from artesian wells. Earthen berms or levees of compact silty clay separate the ponds and ditches from each other. Berm tops have a nominal altitude of 6 ft above sea level, and in fair weather, pond water levels are maintained at about 3 to 4.5 ft and adjacent ditch water levels are about 2 ft. Water depth in the ponds is about 1 to 2 ft. The pond bottoms lie about 2 to 4 ft above sea level and are underlain by several feet of soft, organic-rich mud. Water levels, berms, and pond bottoms for ponds A and E are lower in altitude than those of the other ponds: water levels typically are 1.5 to 3 ft, and the bottom of pond A is at 0.7 ft.

To maintain desired water levels and water quality in the Kii ponds, water from direct rainfall is supplemented by water from free-flowing artesian wells directed through the ponds by a system of pipelines and water-control structures. Ponds G, F, C, and B are fed directly by pipeline, whereas control structures feed pond D from pond F, and pond A from pond B. Pond E is fed through control structures connected to adjacent ditches, and not by the artesian well water. One or two of the Kii ponds are drained annually to burn and remove excess vegetation during the non-nesting season from summer into early fall.

A regional system of shallow ditches (fig. 1) drains the Kahuku coastal plain (essentially, the area seaward of Kamehameha Highway) and conveys the flow of several streams that empty out from the adjacent volcanic uplands. Several of the ditches (Punamano, Kii, Hospital, and Raboy) run through or around Kii Unit (fig. 3), being separated from the Kii ponds by earthen berms or levees. These ditches terminate in an outer ditch (Kii ocean outlet) where water flows to the ocean via a channel that was blasted through a raised limestone shelf that borders the coast.

Within Kii Unit, Punamano, Kii, and Hospital ditches join in confluence behind an earthen berm separating the inner ditch system from the outer ditch (fig. 3). From this confluence, water in the inner ditch flows to the outer ditch through a culvert and one-way tidal duckbill valve if the inner ditch level is higher than the outer ditch; is forced out by a high-capacity, 40-horse-

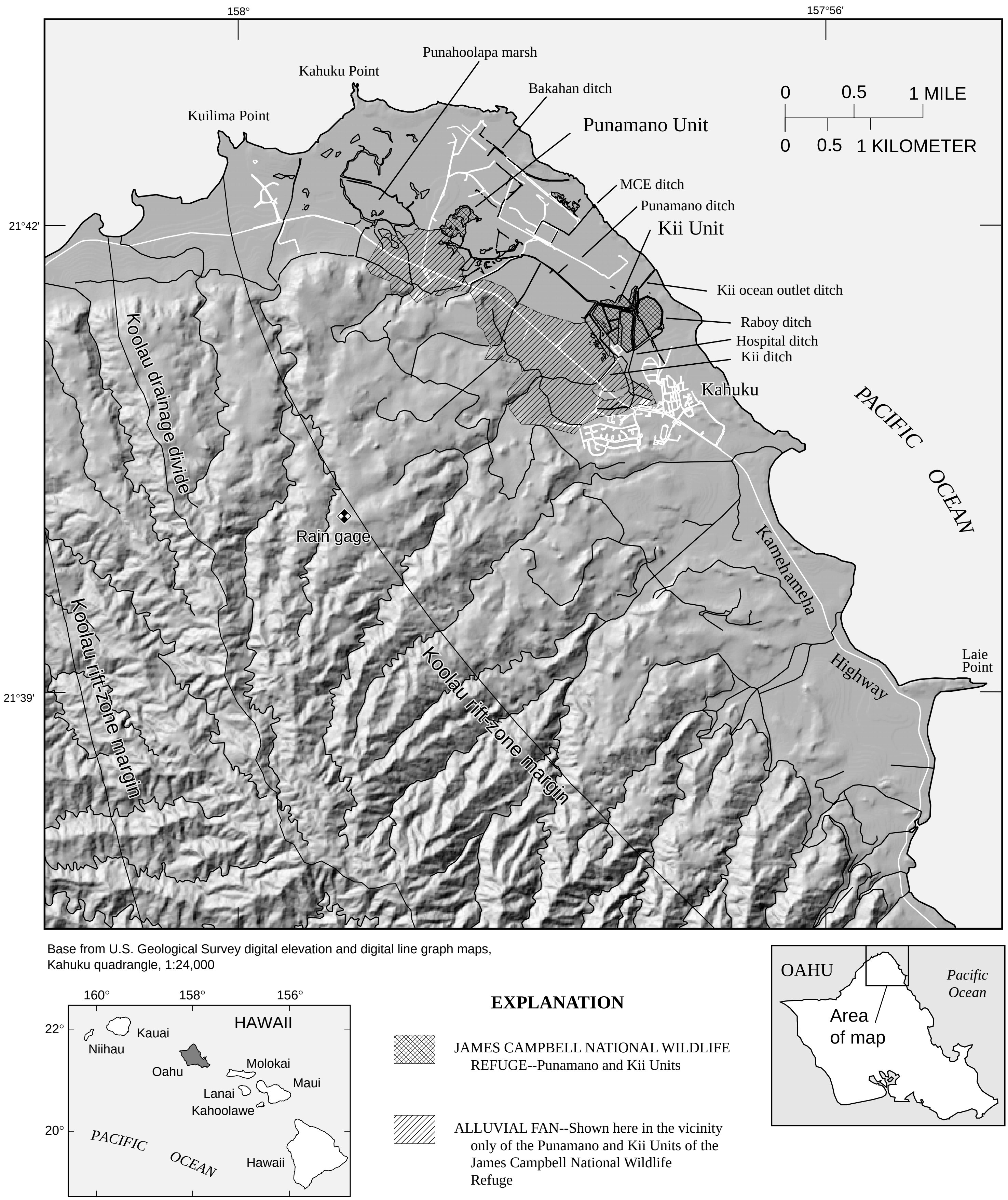
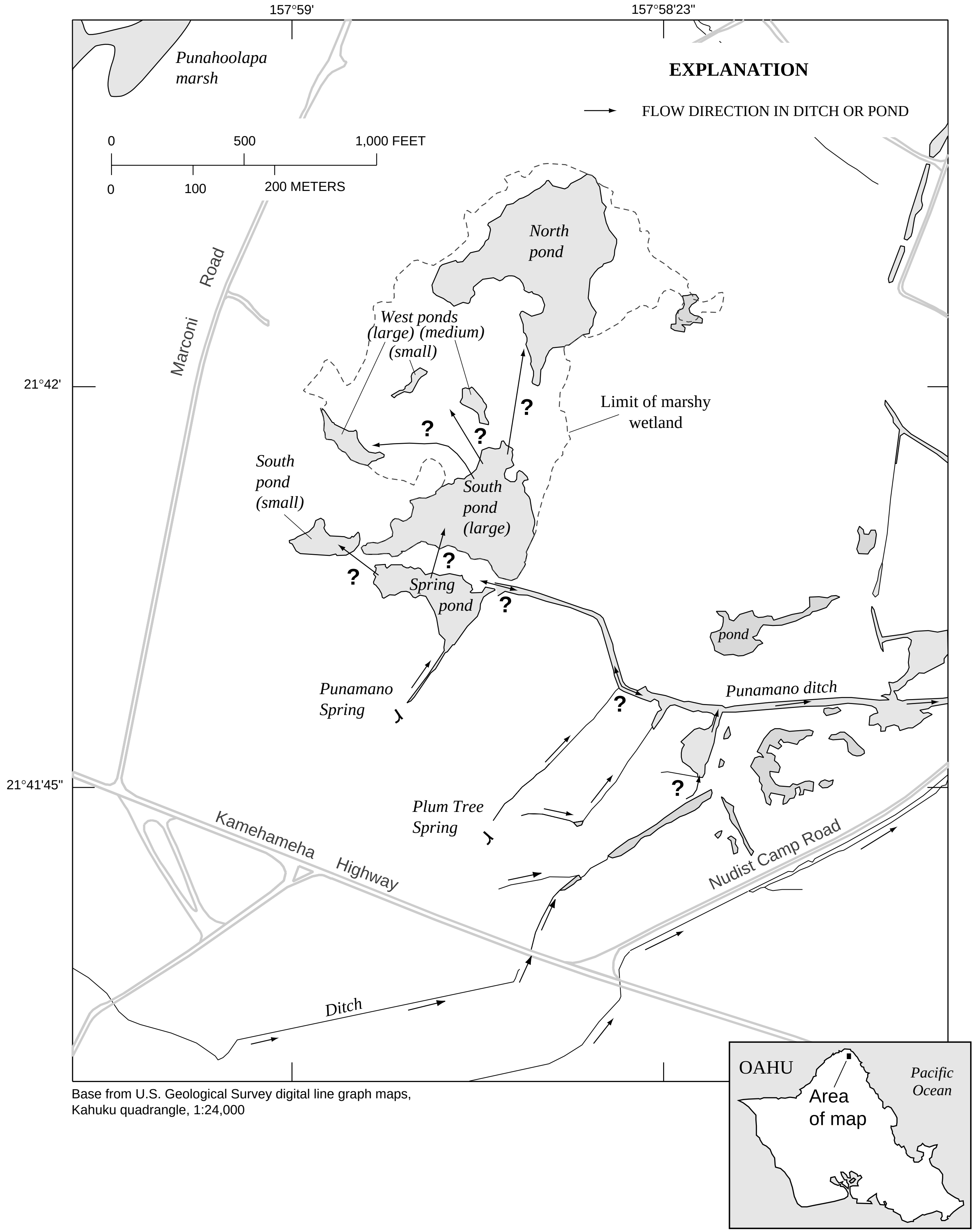


Figure 1. James Campbell National Wildlife Refuge and surrounding area near the town of Kahuku in northern Oahu, Hawaii.



Base from U.S. Geological Survey digital line graph maps,
Kahuku quadrangle, 1:24,000

Figure 2. Punamano Unit of James Campbell National Wildlife Refuge, Oahu, Hawaii.

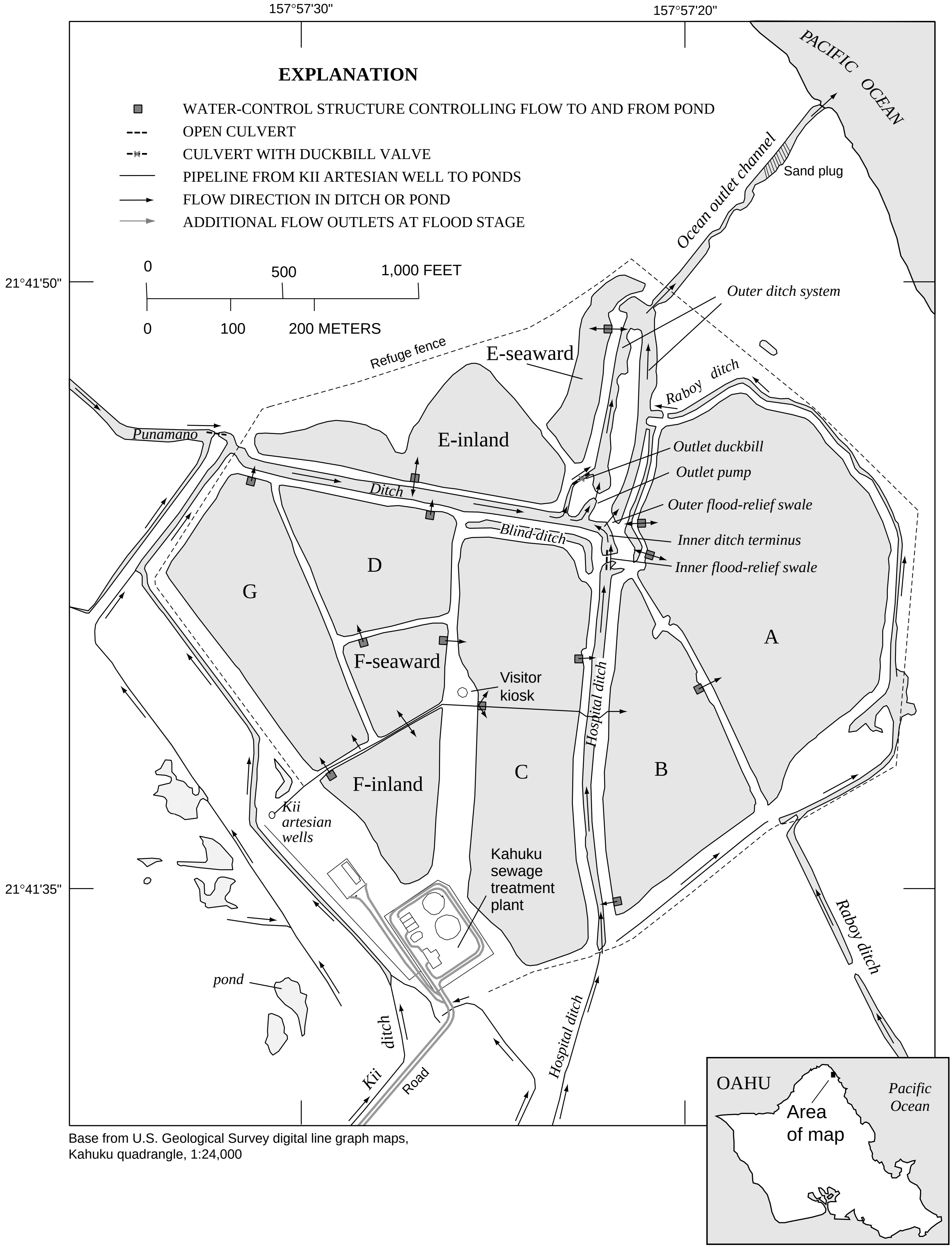


Figure 3. Kii Unit of James Campbell National Wildlife Refuge, Oahu, Hawaii.

power pump that is triggered when the inner ditch level rises above 1.8 ft; or flows freely to the outer ditch at high flood stage, over a low, flood-relief swale in the berm at an altitude of 3.5 ft. Most fair-weather flow and moderate stormflows exit the coastal plain through the Kii ocean outlet. During severe floods that inundate much of the coastal plain, substantial volumes of water may also discharge to the sea through MCE (Marine Culture Enterprises) ditch and the Bakahan ditch, which was re-opened in 1995.

Operation and wildlife habitability of the Refuge depend on its internal hydrology as well as the surrounding environment (fig. 4). Within the Refuge, inflows of freshwater from rainfall, streams, wells, and ground-water sources must be large enough to offset evaporative concentration and keep salinity in the ponds and marshes sufficiently low. Punamano marsh apparently receives considerable ground-water inflow from surficial sediments and from the Koolau aquifer, whereas ponds at Kii probably do not receive appreciable ground-water inflows and so must be supplemented with well water.

Potential water-quality problems are from suspended sediment and chemical residues in agricultural and urban runoff, from saline aquaculture effluents, and from saline water from the ocean (by tidal incursion upstream through the ditch system). Water quality in the Refuge also may be affected by interaction with underlying ground water, which in the surrounding coastal plain is subject to saltwater intrusion, subsurface disposal of domestic wastewater and saline aquaculture effluents, and potentially by chemical residues from fertilizers and pesticides used in the surrounding area.

Purpose and Scope

The purpose of this report is to describe the hydrology and water and sediment quality of the James Campbell National Wildlife Refuge and the hydrologic interaction of the Refuge with the surrounding Kahuku coastal plain. To meet this objective the following steps were undertaken:

1. Streamflow and water levels in ditches entering and leaving the Refuge were analyzed to define the major sources of surface-water inflow, to determine the role that the ocean plays in controlling ditch water levels and outflow rates, and to identify hydraulic factors affecting flooding within and immediately surrounding the Refuge.
2. Hydrogeology, ground-water levels, and salinity surveys were evaluated to qualitatively document ground-water and surface-water interactions in the area of the Refuge. This evaluation forms a basis for describing how water bodies in the Refuge interact with surrounding ditches, ground-water bodies, and the ocean, and for describing potential effects of subsurface disposal of treated wastewater from the Kahuku sewage treatment plant on the Refuge.
3. Transfers of water in and out of the Punamano and Kii Units of the Refuge were summarized in the form of water budgets to quantify the adequacy of the current freshwater supply, particularly during the dry season.
4. Surveys of water quality were done in principal Refuge water sources and selected ponds to evaluate water quality within the Refuge and to provide a baseline description of current water-quality conditions from which potential future changes could be measured. Bottom sediments from selected ponds also were analyzed to determine whether chemical compounds that could affect wildlife have accumulated.

The scope of the work included installation and operation of recording and non-recording gaging stations to measure streamflow and water levels in ditches, ponds, and piezometers, operation of meteorologic stations to measure precipitation and data required to estimate evapotranspiration, surveys to convert all recorded water levels to a common datum, and synoptic salinity surveys and sampling of water and sediment within the Refuge and its principal sources of inflow. Also used in this study were previous geologic studies of the Kahuku area (including documented well logs) as well as water level, precipitation, and well discharge rates provided by the USFWS. Although several gaging stations were established for this study as early as 1995, data analysis focused on the 16-month period from November 1996 through February 1998, when concurrent data were available from most or all of the principal gaging stations. This period included several moderate storms and a full calendar year over which water budgets were computed.

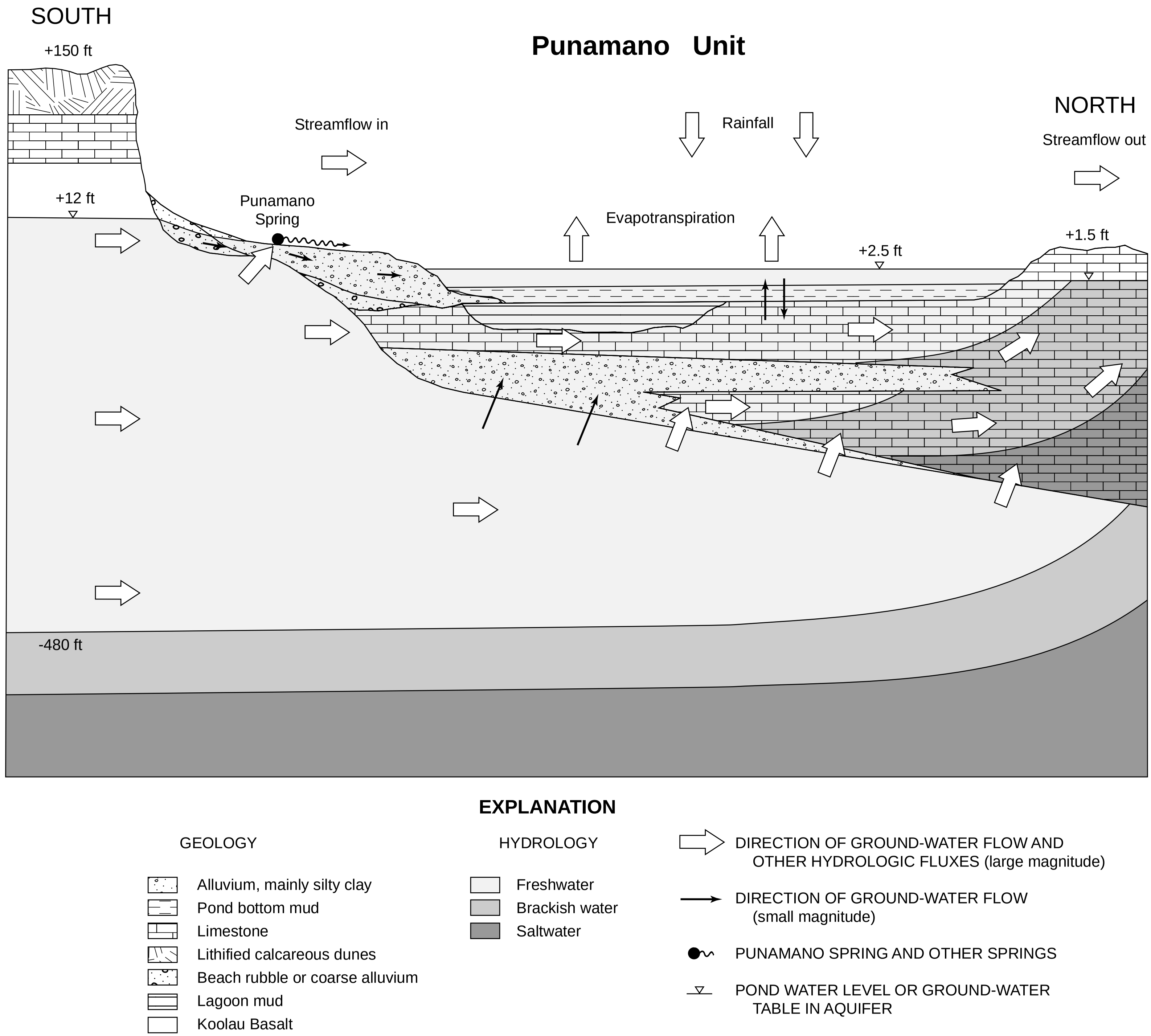


Figure 4. Simplified geology and modes of ground-water/ surface-water interaction at Punamano and Kii Units, James Campbell National Wildlife Refuge, Oahu, Hawaii.

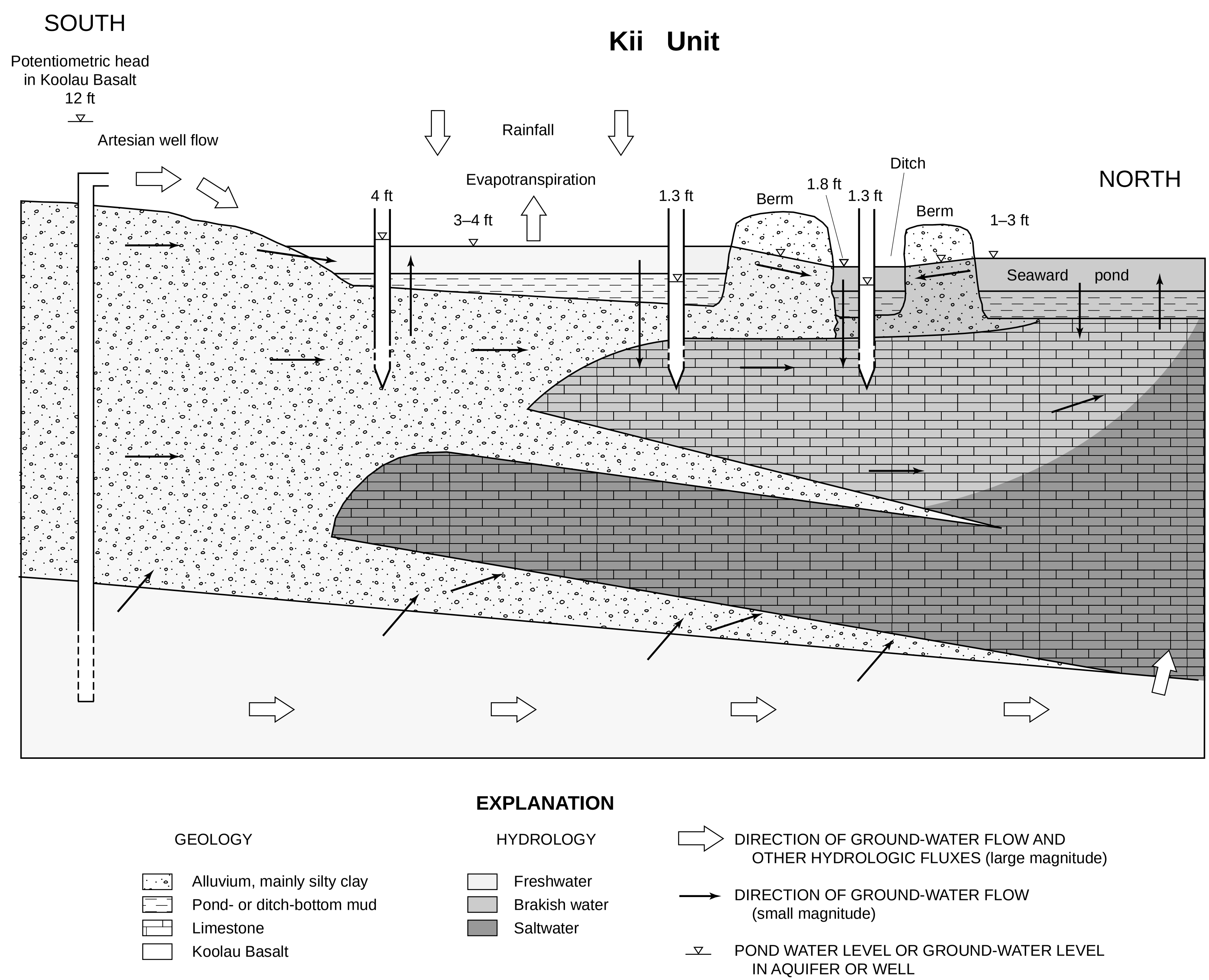


Figure 4. Simplified geology and modes of ground-water/ surface-water interaction at Punamano and Kii Units, James Campbell National Wildlife Refuge, Oahu, Hawaii--*Continued.*

Acknowledgments

Scientists and staff at the U.S. Fish and Wildlife Service (USFWS) field office in Haleiwa, Hawaii, provided valuable assistance and guidance regarding the history and operation of the Wildlife Refuge, and furnished data from their wells, ponds, and meteorology station. Staff at USFWS headquarters in Portland, Oregon, supplied data from water-level recorders at the Refuge ponds. The Estate of James Campbell granted access to Estate lands outside the boundaries of the Wildlife Refuge for reconnaissance surveys of the greater coastal plain. Digital topographic maps of the Kahuku area were furnished by the U.S. Army Corps of Engineers, Pacific Ocean Division, at Fort Shafter, Hawaii. The U.S. Army also granted access to their training area in the Kahuku uplands for construction and operation of a rain gage. The State of Hawaii Department of Transportation issued a permit for a stream-gaging station in a storm drain at Kahuku. Thomas Giambelluca and Michael Nullet, of the University of Hawaii, operated a meteorologic station at Kii Unit under contract.

DESCRIPTION OF THE STUDY AREA

Physiography

The Kahuku landscape (fig. 1) is formed by two principal physiographic provinces: (1) the mountainous Koolau Range in the interior, and (2) a coastal plain seaward of Kamehameha Highway. The Koolau Range is the elongated eroded remnant of a shield volcano that plunges beneath the coastal plain and extends north for many miles beneath the sea. The northernmost terminus of the Range forms the Kahuku uplands. Surficial lavas of Koolau Basalt (Stearns and Vaksvik, 1935; Stearns, 1939) have been deeply weathered, leaving a mantle of readily erodible red soil tens of feet thick over most of the uplands.

The low-lying coastal plain separates the Kahuku uplands from the sea by as much as 1.5 mi. The land surface is less than 10 ft above sea level throughout much of the coastal plain, except along seaward dune ridges. The coastal plain is underlain by marine sediments and basaltic alluvium washed down from the uplands, and by Koolau Basalt at depth. Streams have deposited alluvial fans where they empty out onto the coastal plain at the mouths of their valleys. Two prominent alluvial fans are aligned with Punamano and Kii marshes (fig. 1). The fans are readily noticeable when driving along Kamehameha Highway as broad rises at altitudes of 20 to 30 ft above sea level.

The Koolau Range is deeply dissected by streams that have followed the consequent drainage pattern established on the original domed surface of the Koolau shield volcano. In the Kahuku area, this has resulted in a divergent, radial drainage pattern of the main stream courses, with tributaries branching off in a dendritic pattern. The divergent drainage pattern has generated triangular interfluves of relatively undissected terrain known as flow-slope facets (Wentworth, 1951).

Streams of interest in this study are those that empty onto the coastal plain near the Refuge. Drainage boundaries for selected streams, and for the coastal lowlands surrounding the Refuge, are shown in figure 5, and drainage areas are listed in table 1. These drainage areas cannot be considered definitive. In particular, drainage areas on the coastal plain are ambiguous because variations in topography are subtle. Drainage areas delineated on the coastal plain may merge into larger standing lakes during extreme floods (State of Hawaii Department of Land and Natural Resources, 1971).

Streams in the Kahuku area are short, with steep gradients and small drainage areas. In the uplands, steep terrain and stream gradients cause surface water to run off rapidly, and permeable upland soils permit rapid infiltration of rainfall to the underlying Koolau aquifer. As a result, streamflow near the Refuge is characteristically flashy, with high flood peaks and little base flow. Streamflow is perennial at high altitudes where rainfall is persistent and streams intercept dike-impounded ground water, and at altitudes of 10 ft or less, where streambeds cut into the basal water table in the Koolau aquifer or in sediments.

The drainage area for the Punamano Unit is 0.42 mi^2, which includes 0.34 mi^2 on the coastal plain and 0.08 mi^2 of unnamed upland watershed just inland of Kamehameha Highway. Hoolapa Gulch drains a small watershed to the west of the Punamano Unit into Punahoolapa marsh, from which no apparent outlet to the sea can be identified on topographic maps. Marconi Road separates Punahoolapa marsh from Punamano marsh and likely forms a drainage divide between the two under most runoff conditions. However,

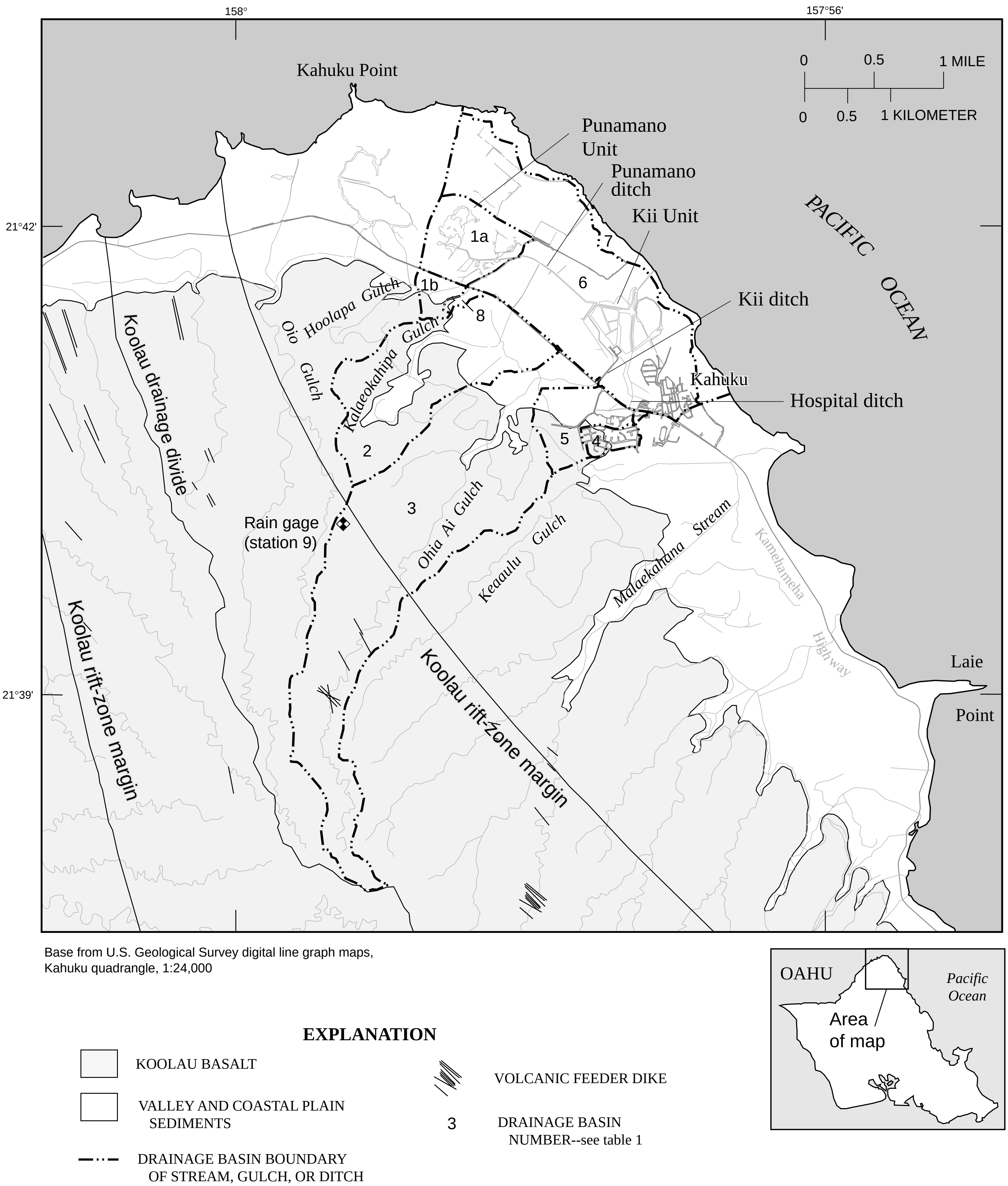


Figure 5. Streams and selected surface drainage boundaries in the vicinity of James Campbell National Wildlife Refuge, Oahu, Hawaii.

Table 1. Drainage areas in the vicinity of the James Campbell National Wildlife Refuge, Oahu, Hawaii

[Areas were determined by geographic information system (GIS), using digital topographic maps provided by the U.S. Army Corps of Engineers, USGS digital line graphs (DLG's) for the Kahuku quadrangle, and a digital version of the geologic map of Oahu (Stearns, 1939); ft^2, square feet; mi^2, square miles]

Drainage area	Drainage area number (fig. 5)	Area	
		(acre)	(mi^2)
Drainage areas for stream-gaging stations			
Station 1 Punamano ditch	1	268	0.419
Station 2 Kalaeokahipa Gulch	2	663	1.036
Station 3 Kii ditch/Ohi Ai Gulch	3	1,585	2.476
Station 4 Kahuku storm drain	4	51	0.080
Station 5 Hospital ditch	5	173	0.270
Other areas of interest			
Coastal plain minus sand and Punamano	6	1,081	1.689
Sand (dunes and beach)[1]	7	172	0.269
Nudist Camp Road ditch inland	8	14	0.022
Punamano (Station 1 seaward)	1a	217	0.339
Punamano inland (Station 1 inland)	1b	51	0.080
Selected totals			
Uplands (inland of highway)		2,537	3.964
Coastal plain (seaward of highway)		1,470	2.297
Coastal plain minus sand		1,298	2.028
Total area		4,007	6.261
Total minus sand		3,835	5.992

[1] Considered here as not contributing runoff to the interior coastal plain or the Refuge, owing to high infiltration capacity and proximity to the coast

Punahoolapa marsh may drain eastward to Punamano marsh and ditch during extreme floods that overtop Marconi Road.

Several streams drain to the Kii Unit of the Refuge. Ohia Ai Gulch has a drainage area of 2.48 mi^2 that extends into the Koolau rift zone, all the way to the crest of the Koolau range (fig. 5). Seaward of Kamehameha Highway, Ohia Ai Gulch is known as Kii ditch, which joins with Punamano ditch prior to entering the Kii Unit at its west boundary. Kalaeokahipa Gulch drains an area of 1.04 mi^2 inland of Kamehameha Highway into Punamano ditch, which flows east to the Kii Unit. Also draining to Kii Unit is Hospital ditch, a 0.27 mi^2 watershed that is bordered by Kahuku Hospital, and runoff from a residential subdivision that drains to Kahuku storm drain (drainage area 0.08 mi^2). The next valley to the east, Keaaulu Gulch, does not drain to the coastal lowlands that encompass the Refuge: its stream follows a path through low hills behind a residential subdivision, joins Malaekahana Stream just inland of Kamehameha Highway, and discharges directly to the ocean south of Kahuku.

Climate

The Kahuku area is subject to a subtropical climate characterized by mild temperature, moderate humidity, prevailing northeasterly trade winds, and extreme variation in rainfall over short distances. Climate varies spatially with altitude and in relation to prevailing and local winds. Mean annual temperature is about 76°F in the coastal lowlands of Oahu, decreasing to less than 70°F in the mountainous uplands (Blumenstock and Price, 1967).

Rainfall and cloud cover increase with altitude and in the inland direction, following an orographic pattern established as moist oceanic air is forced up and over the Koolau Range by persistent northeasterly trade winds or sporadic southwesterly winds that accompany winter low-pressure systems. Median annual rainfall increases from about 39 inches at the town of Kahuku, to about 150 inches at the headwaters of Ohia Ai Gulch, to over 300 inches near the crest of the Koolau Range farther south (State of Hawaii Department of Land and Natural Resources, 1982; Giambelluca and others, 1986). Mean annual rainfall over the open ocean near Oahu has been estimated to be about 25 inches (Blumenstock and Price, 1967).

Rainfall on Oahu is seasonal, with wetter winter months from October through April, and drier summer months from May through September. The uplands receive a steady contribution of tradewind rainfall throughout the year, supplemented by intense, episodic rains from winter cold fronts, convective disturbances associated with upper-atmosphere low-pressure systems, and occasional hurricanes. The coastal plain receives a lesser proportion of total rainfall as tradewind rain and a much greater proportion as episodic, winter rain.

Evaporation varies inversely with cloud cover and rainfall, and is greatest on the sunny coastal plain and least in the rainy uplands. On the Kahuku coastal plain, Ekern and Chang (1985) report annual pan evaporation to be 82.2 in. for the period 1960–65.

Ekern and Chang (1985) also provided an empirical fitting equation for Oahu that can be used to estimate annual pan evaporation (Evap) from median annual rainfall (with both in inches):

$$\log \text{Evap (in/yr)} = 1.99 - 0.003\ \text{Rain (in/yr)} \qquad (1)$$

Using this equation, annual pan evaporation is estimated to be about 35 in. at the headwaters of Ohia Ai Gulch.

Land Use

The Kahuku area is primarily rural. Land use includes forest, agriculture, and aquaculture, with light suburban development clustered in the town of Kahuku. Two golf courses are located on the Kahuku coastal plain: one occupies high dune fields just east of the town of Kahuku and the other one adjoins an extensive resort at the west end of the coastal plain near Kuilima Point, occupying the former Punahoolapa marsh.

Gently sloping areas in the lowlands, and in the uplands to altitudes of about 200 ft, were cultivated for sugarcane by Kahuku Plantation Co. from 1890 through 1971. By 1940, ground-water withdrawal for sugarcane irrigation was averaging about 30 Mgal/d (million gallons per day; Takasaki and Valenciano, 1969). After the end of sugar cultivation, these lands were put to use for ranching, diversified-crop farming, and aquaculture. Residential development is more widespread now than in plantation times, but the area is still comparatively rural.

Aquaculture flourished on the coastal plain during the 1970's to mid-1990's and included a mix of both freshwater and saltwater products such as prawns, shrimp, oysters, and fish stock. Most of the aquaculture companies eventually halted production. One of the largest of the operations ceased production in 1994, leaving extensive aquaculture ponds lying dormant on the broad alluvial fan between Nudist Camp Road and Kii Unit and between Kamehameha Highway and Punamano ditch. A tract of ponds immediately southwest of Kii Unit had been under freshwater aquaculture, whereas the remainder of the area had been under saltwater aquaculture (fig. 6).

Inland, the rugged, mountainous terrain is mostly forested conservation land, typically designated as watershed preserves. The U.S. Army uses parts of the Kahuku uplands as a training area.

DATA-COLLECTION PROGRAM

Field data were collected to furnish estimates of relevant surface-water, ground-water, and atmospheric-water fluxes, and to characterize the quality of water in ponds and water sources within the Refuge. The data-collection program included a fixed network of 39 surface-water, ground-water, meteorology, and water- and sediment-chemistry stations, as well as a salinity/seepage survey that included measurements at 107 sites.

The stations that make up the fixed data-collection network are listed in tables 2 and 3, and are shown in figures 6 through 9 (the location of upland rain gage station 9 is shown in fig. 5). Concurrent records were obtained from primary surface-water and meteorology stations 1 through 11, 21, 35, and 36, and from ground-water station 6 for a period of 1 year, from January through December 1997. Several of these stations were in operation before or after 1997 and provided auxiliary data for significant events such as the severe storm of November 14, 1996. Records were obtained at ground-

Table 2. Fixed data-collection stations and benchmarks included in the hydrologic and meteorologic data network at James Campbell National Wildlife Refuge, Oahu, Hawaii

[USFWS, U.S. Fish and Wildlife Service; USGS, U.S. Geological Survey; USCGS, U.S. Coast and Geodetic Survey; continuous recorders were operated at stations marked "Y"; precise altitudes were surveyed to most stations (except 9 and 35–37) and are available in files of the U.S. Geological Survey, Honolulu, Hawaii; datum for altitudes is mean sea level; ft, feet; --, not applicable; stations are shown on figures 6–8]

Station number	Station name	Station type	Location or description	Type of measurement; remarks	Recorder	Source of data
Primary surface-water and meteorology stations						
1	Sta 1	Flow meter	Punamano ditch duckbill	Ditch level, discharge, chemistry	Y	USGS
2	Sta 2	Stage gage	Kalaeokahipa Gulch	Stream level, discharge	Y	USGS
3	Sta 3	Stage gage	Kii ditch/Ohia Ai Gulch	Ditch level, discharge, chemistry	Y	USGS
4	Sta 4	Flow meter	Kahuku storm drain	Ditch level, discharge, chemistry	Y	USGS
5	Sta 5	Stage gage	Hospital ditch / Mill ditch	Ditch level only	Y	USGS
7	Sta 7	Flow meter	Kii outlet duckbill/inner ditch	Ditch level, discharge	Y	USGS
8	Sta 8	Stage gage	Kii ocean outlet/outer ditch	Ditch level only	Y	USGS
9	Sta 9	Rain gage	Upland rain gage	Rain	Y	USGS
10	Sta 10	Met station	University of Hawaii meteorology station	Rain, evaporation, temperature, windspeed, humidity, solar radiation, soil heat flux	Y	UH
11	Sta 11	Pump timer	Kii outlet pump	Ditch level, pump on/off time, barometric pressure	Y	USGS
21	Staff B	Staff gage	Pond B at gate to pond A	Pond level	Y	USFWS, USGS
35	USFWS Met	Met station	USFWS meteorology station	Rain, temperature, humidity, wind speed and direction, barometric pressure	Y	USFWS
36	Puna pond	Staff gage	Punamano north pond	Pond level, chemistry	Y	USFWS
Ground-water stations						
6	Sta 6	Well meter	Kii artesian wells; flow meters	Ground-water withdrawal, chemistry	--	USFWS
12	Sta 12	Piezometer	Kii Pond D next to Punamano ditch	Ground-water and pond level, chemistry	Y	USGS
13	Sta 13	Piezometer	Punamano ditch next to pond D	Ground-water and ditch level	Y	USGS
14	Sta 14	Piezometer	Kii Pond D inland	Ground-water and pond level	--	USGS
15	Sta 15	Piezometer	Kii Pond C next to Hospital ditch	Ground-water and pond level	Y	USGS
16	Sta 16	Piezometer	Hospital ditch next to pond C	Ground-water and ditch level	--	USGS
17	Sta 17	Piezometer	Pond A next to outer ditch	Ground-water and pond level	Y	USGS
18	Sta 18	Piezometer	Pond F near sewage treatment plant	Ground-water and pond level	--	USGS
19	STPwell	Monitoring well	Kahuku sewage treatment plant	Ground-water level	--	USGS
Supplemental surface-water stations and miscellaneous sites						
20	Staff A	Staff gage	Pond A at gate to outer ditch	Pond level	--	USFWS, USGS
22	Staff C	Staff gage	Pond C at gate to Hospital ditch	Pond level	--	USFWS, USGS
23	Staff Ck	Staff gage	Pond C at kiosk gate	Pond level	--	USFWS, USGS
24	Staff D	Staff gage	Pond D at gate to Punamano ditch	Pond level	--	USFWS, USGS
25	Gate E-in	Gate	Pond E gate to inner (Punamano) ditch	Pond level	--	USGS
26	Gate E-out	Gate	Pond E gate to outer ditch	Pond level	--	USGS
27	Staff F	Staff gage	Pond F at gate to pond G	Pond level	--	USFWS, USGS
28	Staff G	Staff gage	Pond G at gate to Punamano ditch	Pond level	--	USFWS, USGS
29	Gate A-out	Gate	Pond A gate to outer ditch east arm	Pond level	--	USGS
30	Gate B-H	Gate	Pond B gate to Hospital ditch	Pond level	--	USGS
31	Gate F-C	Gate	Pond F gate to pond C near kiosk	Pond level	--	USGS
32	Gate F-D	Gate	Pond F gate to pond D	Pond level	--	USGS
33	Swale-in	Relief swale	Inner swale Hospital to Punamano ditch	Ditch level; altitude 3.43 ft	--	USGS
34	Swale-out	Relief swale	Outer swale Punamano to outer ditch	Ditch level; altitude 3.53 ft	--	USGS
37	Puna spring	Spring	Punamano Spring	Chemistry	--	USGS
44	Pond C chem	Pond	Kii pond C next to Punamano ditch	Chemistry	--	USGS
45	Hosp chem	Ditch	Hospital ditch at Kii Refuge fence	Chemistry	--	USGS
Benchmarks						
38	BM-kiosk	Benchmark	Kii Unit visitor kiosk	USFWS benchmark; altitude 6.00 ft	--	USGS
39	BM-A	Benchmark	Near Kii pond A staff gage	USFWS benchmark; altitude 5.20 ft	--	USGS
40	BM-B	Benchmark	Kii pond B staff gage	USFWS benchmark; altitude 6.06 ft	--	USGS
41	BM-C	Benchmark	Kii pond C staff gage	USFWS benchmark; altitude 6.86 ft	--	USGS
42	Windmill	Benchmark	Kii, at Punamano ditch and kiosk berm	Temporary benchmark; altitude 5.54 ft	--	USGS
43	BM-23	Benchmark	Highway bridge at Hoolapa Gulch	USCGS benchmark; altitude 22.66 ft	--	USCGS

water stations 12 through 18 for the 4 month period from September 1997 through December 1997. The majority of the remaining stations were not recording stations and were read manually throughout the study period.

Precise altitudes were surveyed to all water-level measuring points so that water levels could be expressed as absolute altitudes relative to the common datum of mean sea level. Altitude surveys were run from a single, U.S. Coast and Geodetic Survey benchmark on the Hoolapa Gulch bridge abutment at Kamehameha Highway (station 43) to ensure consistency of results.

Surface-Water Stations

The primary network of surface-water stations for this study were stations 1 through 5, 7, 8, and 11, most of which were equipped with continuous data recorders operated by the USGS, and pond-stage gages at stations 21 and 36, operated by USFWS (fig. 6). Supplemental stations 20 and 22 through 34 included staff gages and water-control structures within the various ponds, and two flood-relief swales in earthen berms that separate principal ditches at Kii Unit (fig. 7).

Stations 2, 3, 5, and 8 were stream-stage gages. At this type of gage, a low check dam with a v-notch weir across the stream acts as a stage-discharge control. An upstream stilling well has intakes, hydraulically connected to the stream, that ensure water levels in the well are the same as those in the stream. A sensor continuously measures water levels in the protected environment inside the stilling well. Electronic data recorders store the output from the water-level sensor, typically at 10-minute intervals.

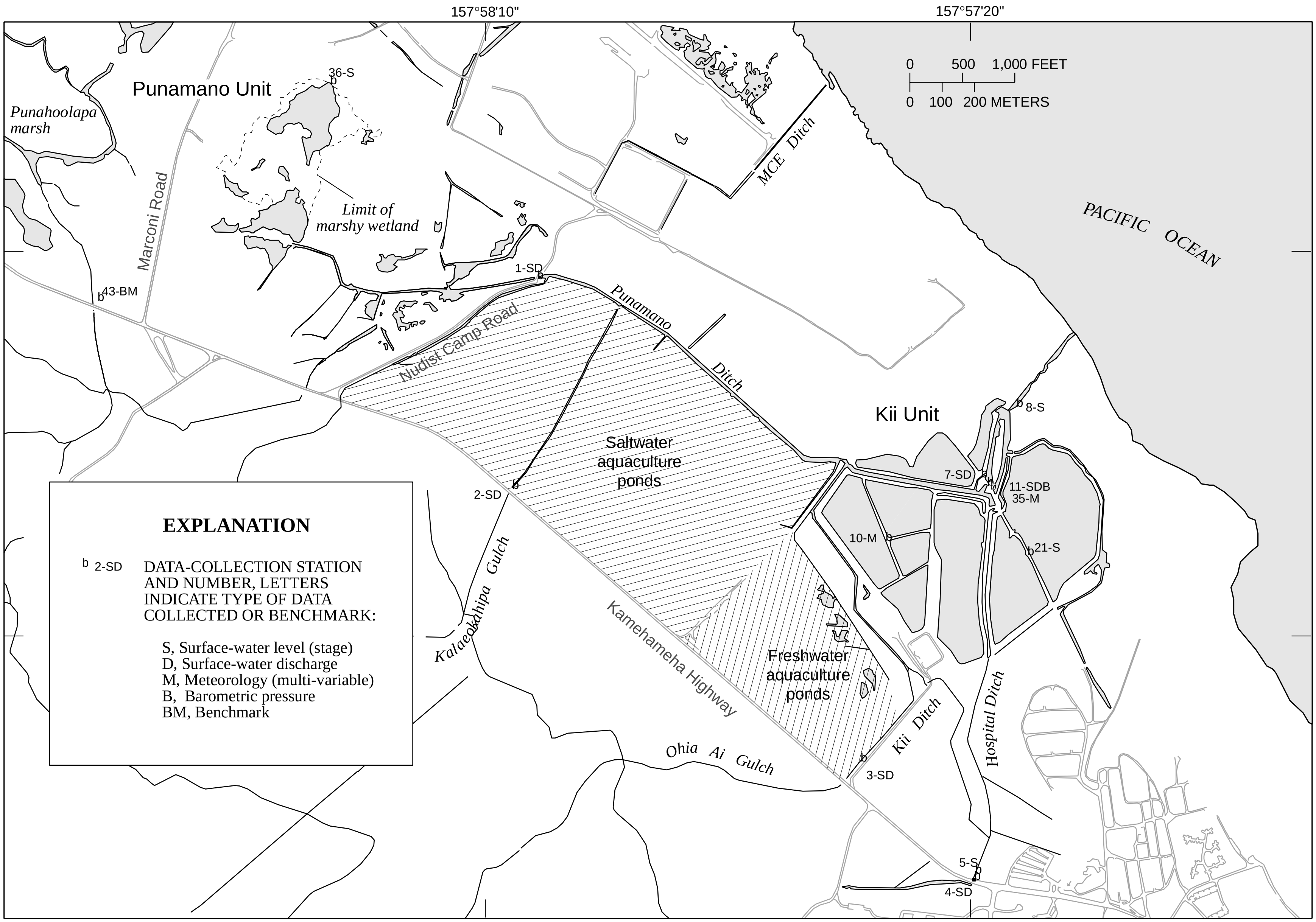
A rating curve is developed for the station to convert the records of stream stage to stream discharge. Once a sufficient number of discharge measurements are made, a rating curve can be plotted relating stream stage to discharge. The discharge measurements must be made over sufficiently broad ranges of stage and discharge in order for a valid rating curve to be developed.

At station 2 on Kalaeokahipa Gulch, the entire stream gage was washed away by the flood of November 14, 1996 and no record was available until the station was rebuilt on December 18, 1996. The lack of continuous submergence of the water-level sensor during periods of no flow and frequent recorder malfunctions limited the periods when discharge was quantifiable at station 2 to brief periods during storms. At station 5 on Hospital ditch, discharge was not quantified because the number of storms measured was insufficient to develop an accurate rating curve. Station 8 was designed as a stage-only gage, because ocean tides cause frequent reversals of flow direction in the Kii ocean outlet making it impossible to develop a unique rating curve.

Stations 1, 4, and 7 were located in cylindrical culverts or storm drains in which doppler-ultrasonic flow meters were installed. Station 4 was at a storm drain that delivers runoff into Hospital ditch from a nearby residential neighborhood in the town of Kahuku. Stations 1 and 7 measured channel ditchflows beneath roads at locations where the culverts are outfitted with one-way, tidal-control, "duckbill" valves on their downstream ends. The valves are designed to help prevent backflow and facilitate downstream flow through the culvert. The duckbill valve at station 7 was installed to prevent incursion of saline water into the inner ditch system that borders the freshwater ponds at Kii Unit. Similarly, the duckbill valve at station 1 was installed to prevent backflow of potentially brackish-to-saline water from the lower reaches of Punamano ditch up into Punamano Unit and environs.

The doppler-ultrasonic flow meters at stations 1, 4, and 7 used multiple sensors affixed to the inside of the culvert. One sensor was a bubbler tube connected to a pressure transducer that measured water level. Water level was converted into a wetted area on the basis of known culvert geometry, which at these stations was cylindrical. Another sensor emitted an ultrasonic pulse and sensed the timing of the return pulse using the doppler principle to compute the average velocity of water in the culvert. The meter then multiplied the average velocity by the wetted area of the culvert to compute flow at 10-minute intervals. The doppler flow meters were capable of sensing reversals of flow in the culverts and could measure flow rates in both the upstream and downstream directions.

Station 11 was equipped with a continuous recorder that measured barometric pressure, inner (Punamano) ditch level, and pump on and off times for the Kii outlet pump. The 40 horsepower pump at station 11 was rated at a nominal pumping rate of 12,000 gal/min. By recording the pump on and off times,



Base from U.S. Geological Survey digital line graph maps,
Kahuku quadrangle, 1:24,000

Figure 6. Primary network of surface-water and meteorologic stations, James Campbell National Wildlife Refuge, Oahu, Hawaii (also included in the primary network is rain gage station 9 shown on figure 5).

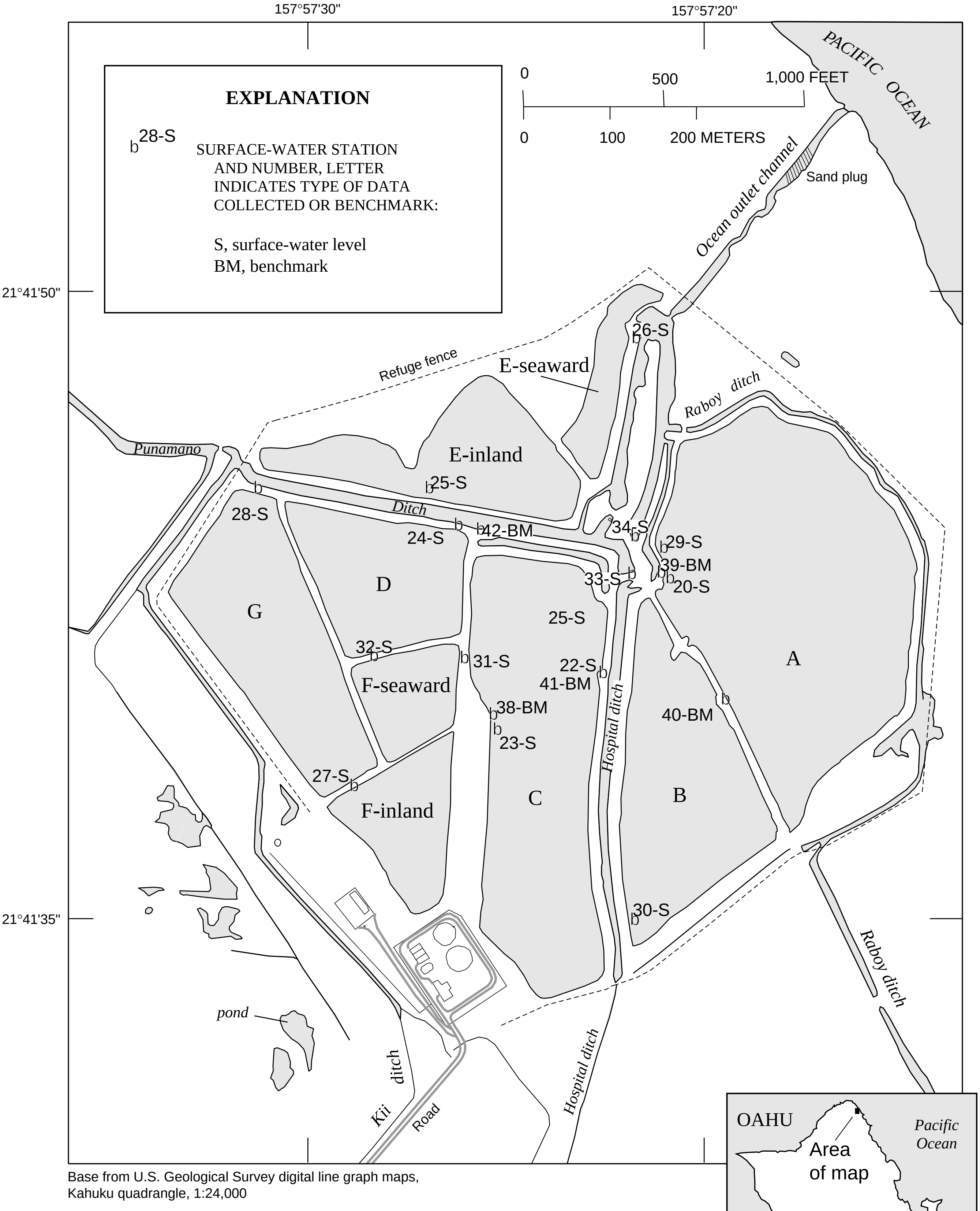


Figure 7. Supplemental surface-water stations and benchmarks at the Kii Unit, James Campbell National Wildlife Refuge, Oahu, Hawaii.

pumping duration can be computed. Duration was then multiplied by the nominal pumping rate to estimate discharge from the inner ditch system through the pump. About 6 weeks of record were lost to recorder malfunction in 1997. However the pumpage record at station 11 was reconstructed using the water-level data at nearby station 7 to estimate pump on and off times. The pump at station 11 is operated for two primary reasons: to assist the nearby outlet culvert, at station 7, in transferring water out of the inner ditch system and into the outer ditch and subsequently into the ocean (this is particularly important during stormflows when the capacity of the outlet culvert is frequently exceeded); and to transfer water out of the inner ditch system when water will not flow out unassisted, for example during high tides, when the water level in the outer ditch is higher than that in the inner ditch and the station 7 duckbill valve remains closed.

Intermittent, manual readings of water levels were made at stations 20 and 22 through 34 to provide synoptic surveys of pond and ditch levels throughout Kii Unit (fig. 7). Water levels were measured at graduated staff gages maintained by USFWS in each of the Kii ponds, at water-control structures, and at flood-relief swales in earthen berms. Swale-in (station 33) is the "inner" flood-relief swale separating Hospital ditch from Punamano ditch near the outlet pump. A culvert runs beneath this swale, so water can flow freely between the two inner ditches even when the swale is not overtopped. When ditch levels rise above the low point in the inner swale (altitude 3.4 ft), the swale is overtopped and water can flow between the ditches by this route as well. Swale-out (station 34) is the "outer" flood-relief swale separating the inner ditch (Punamano ditch) from the outer ditch. The altitude at its low point is 3.5 ft. When ditch levels exceed this level the swale is overtopped and water can flow freely between the inner and outer ditches.

Meteorology Stations

Meteorologic data were collected at stations 9, 10, and 35 (figs. 5 and 6). Station 9 was a recording rain gage, located at an altitude of 580 ft in the Kahuku uplands, that recorded accumulated rainfall at 10-minute intervals. Station 10 was operated by University of Hawaii climatologists to collect the data required to compute estimates of potential evaporation using the Penman method (Penman, 1948). Multiple sensors at the station measured rainfall, air temperature, relative humidity, wind speed, net solar radiation, and soil heat flux. The electronic recorder at the station read each sensor every 5 seconds and recorded mean values every 10 minutes. The data were further summarized to hourly and daily means (totals for rainfall) and Penman's equation was applied to compute potential evaporation (T.W. Giambelluca and M.A. Nullet, University of Hawaii, written commun., 1998). Station 35 was a continuous-recording station operated by USFWS to collect rainfall and other meteorologic data in the vicinity of the Refuge. Rainfall data from station 35 were substituted for missing rainfall data at station 10 for multiple gaps in the record.

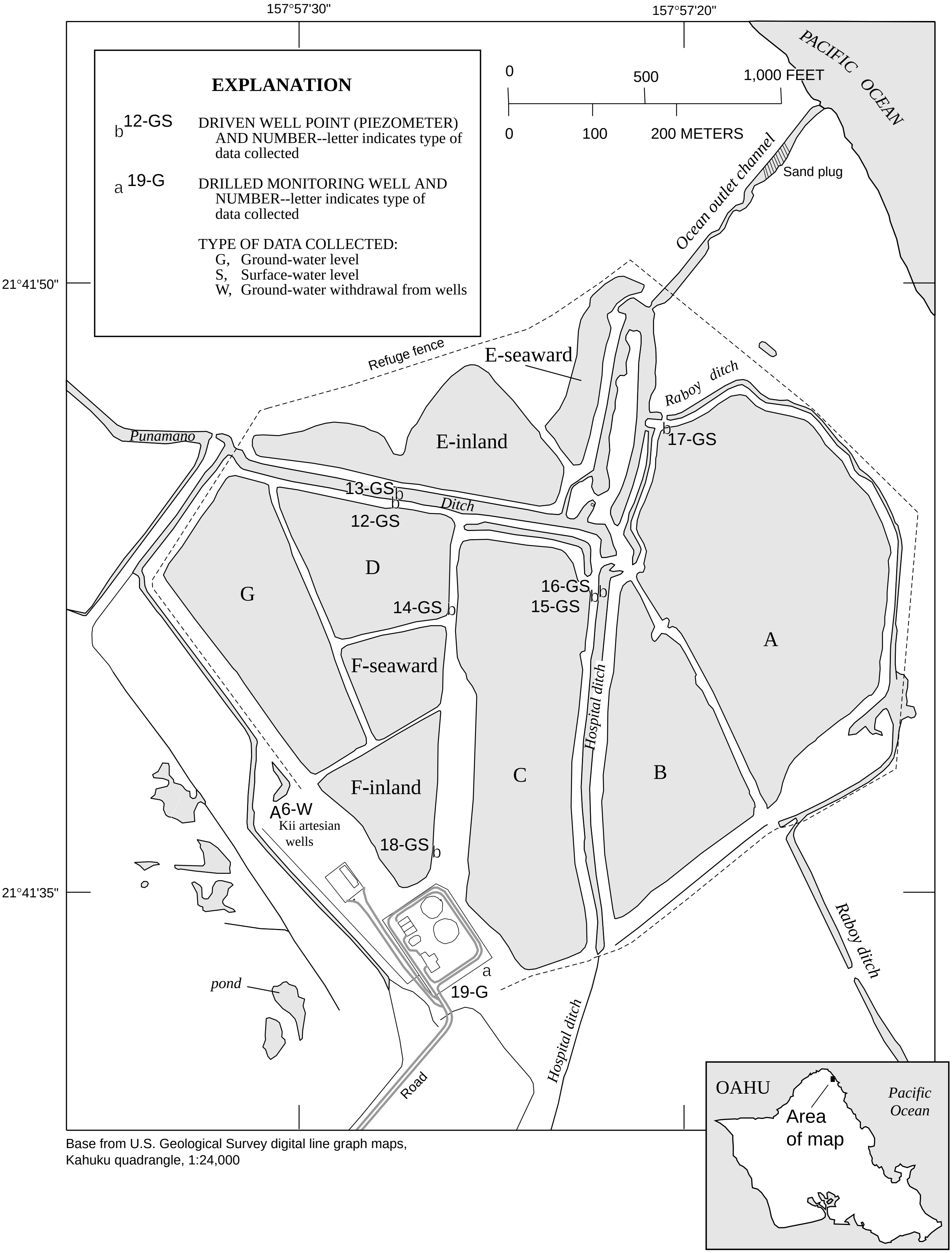
Ground-Water Stations

Stations 12 through 18 (fig. 8) were steel piezometers driven into ponds and ditches at the Kii Refuge. Station 19 was a monitoring well that had been previously installed near the Kahuku sewage treatment plant. Station 6 (fig. 8) refers to the Kii artesian wells, where the USFWS installed totalizing flow meters in 1996 that provide a monthly record of ground-water flow from the three wells. Water from the Kii artesian wells is used to maintain water levels within all ponds in the Kii Unit except for pond E.

Ground-water levels inside the piezometers were recorded along with concurrent measurements of pond- or ditch-water levels in a separate stilling well attached to the piezometer riser pipe. Electronic recorders with dual pressure transducers were installed at four of the piezometers (stations 12, 13, 15, and 17) and operated to record water levels at a 10-minute interval. Manual measurements were made at the other piezometers (stations 14, 16, and 18) and at the station 19 monitoring well. Manual measurements were typically made as part of a synoptic survey done on a single day.

Water- and Sediment-Quality Stations

Samples of water and bottom sediment were collected for analysis of organic and inorganic chemical constituents during two surveys, a dry season survey and a wet-season survey (table 3 and fig. 9). The dry season survey consisted of water samples collected from five sites and sediment samples from three sites. Water sampling sites included the primary sources of



Base from U.S. Geological Survey digital line graph maps, Kahuku quadrangle, 1:24,000

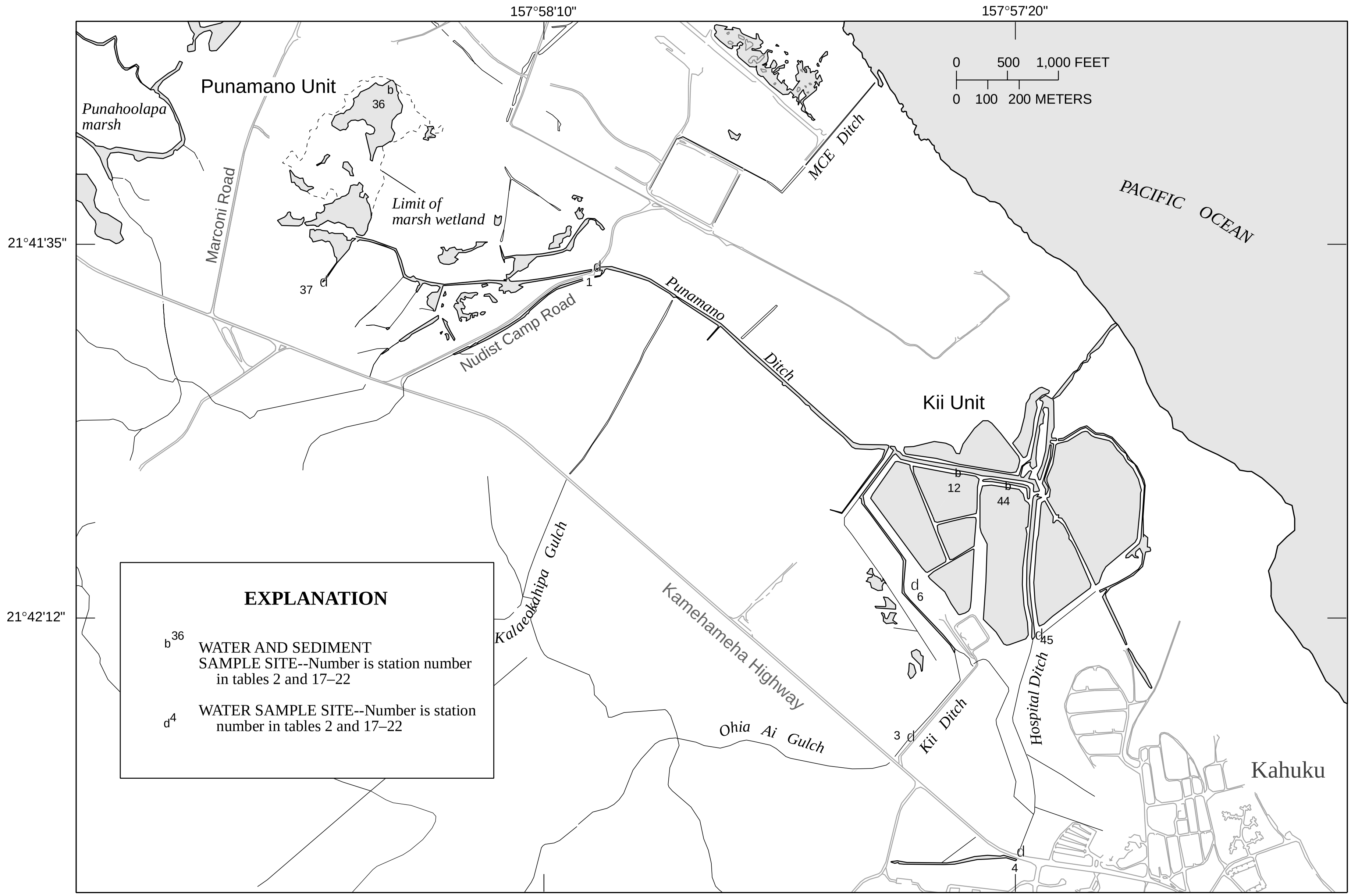
Figure 8. Ground-water stations at the Kii Unit, James Campbell National Wildlife Refuge Oahu, Hawaii.

Table 3. Water and sediment samples collected for organic and inorganic chemical analyses, James Campbell National Wildlife Refuge and vicinity, Oahu, Hawaii

[Sampling sites are shown on figure 9]

Sample designation	Station number	Location or description
Dry-season sampling, November–December 1994		
Water samples, November 22, 1994:		
A	37	Punamano Spring
B	36	Punamano north pond
C	44	Kii pond C next to Punamano ditch
D	12	Kii pond D next to Punamano ditch
E	6	Kii artesian wells
Pond-bottom sediment samples, December 28, 1994:		
F	36	Punamano north pond, top of sediment core
G	36	Punamano north pond, bottom of sediment core
H[1]	44	Kii pond C next to Punamano ditch, grab sample, top of sediment
I[1]	12	Kii pond D next to Punamano ditch, grab sample, top of sediment
Wet-season sampling, March 13–14, 1997 (all water samples)		
A	37	Punamano Spring
B	36	Punamano north pond
C	44	Kii pond C next to Punamano ditch
D	12	Kii pond D next to Punamano ditch
E	6	Kii artesian wells
F	3	Kii ditch at station 3
G	45	Hospital ditch at Kii Refuge fence
H	4	Kahuku storm drain at station 4
I	1	Punamano ditch at station 1
J	6	Duplicate sample from Kii artesian wells

[1] Sample designation and collection method correspond to organic analyses. Cores were also collected at these sites and were subsampled at top and bottom for inorganic major-element and trace-element analyses.



Base from U.S. Geological Survey digital line graph maps, Kahuku quadrangle, 1:24,000

Figure 9. Sites sampled for inorganic and chemical analysis of water and pond-bottom sediment, James Campbell National Wildlife Refuge, Oahu, Hawaii.

inflow to the Refuge during the dry season (Punamano Spring and Kii artesian wells) and representative Refuge ponds (Punamano north pond and Kii ponds C and D). Sediment sampling sites were located in Punamano north pond and Kii ponds C and D. The wet-season survey consisted of water samples collected from nine sites. Water sampling sites included the same five sites sampled during the dry season as well as four sites located on ditches and storm drains in the vicinity of surface-water gaging stations 1, 3, 4, and 5 located on Punamano ditch, Kii ditch, Kahuku storm drain, and Hospital ditch respectively.

An extensive salinity survey of ponds and ditches was made throughout the greater coastal plain, concentrating on the Kii and Punamano Units of the Refuge, the connecting Punamano ditch, and known springs at and near Punamano and Plum Tree Springs. The survey was made using specific conductance as a surrogate of salinity and was designed as an attempt to locate areas of measurable ground-water seepage by detecting abrupt contrasts in specific conductance or temperature. Site locations and the salinity survey results are discussed in greater detail in the section of the report titled "Ground-water/surface-water interaction."

STREAMFLOW

Water-Level Fluctuations in the Gaged Surface-Water Bodies

Water-level hydrographs for streams, ditches, and selected ponds are shown in figures 10 and 11 for the period October 1996 through February 1998. This period encompasses the year-long span of concurrent record in 1997, as well as a severe storm in November 1996 and data collected in January and February 1998. The water-level hydrographs include all data collected at 10- and 15-minute intervals. Although some detail is obscured by the compressed scales in figures 10 and 11, the hydrographs still serve to demonstrate several key water-level relationships of importance to the Refuge. Hydrographs with expanded time scales are used to provide greater details in later sections of the report.

The hydrographs have different patterns that reflect characteristics of the water bodies they measure, such as the runoff response for upland watersheds, downstream hydraulic factors that limit water movement, storage characteristics of the water bodies themselves, and management practices.

Stations 2 through 5 are upland gages, and their hydrographs have short-duration spikes that quickly return to a fairly consistent base level. These stations lie just seaward of Kamehameha Highway (fig. 6), on an alluvial fan that forms a transition from uplands to coastal lowlands. Stream channels at these stations are narrow and transmit flashy streamflows from the uplands on to the lower coastal plain. The streams are intermittent or nearly so: station 2 is truly intermittent, having a dry channel much of the year, whereas stations 3 and 5 were perennial during the study but had only a trickle of flow during dry periods. Flow from the storm drain at station 4 also is intermittent.

The rest of the stations are lowland gages (fig. 6A), and their hydrographs have broader storm peaks and much longer recession times in returning to fair-weather base levels than upland stations 2 through 5. The timing and speed of outflow from the lowland water bodies is governed by differences between upstream and downstream water levels and the amount of water that has been stored in water bodies and surficial materials upstream of the gages. Backwater resistance may be imposed by high downstream water levels, potentially suppressing outflow in comparison to free drainage conditions. These factors combine to produce hydrographs that are delayed and subdued in range compared with the upland gages.

Examples of backwater are at stations 1 and 36 when downstream Punamano ditch stage was the same or greater than upstream stage. When that happened, the duckbill valve at station 1 would not open and there would be no outflow of water from Punamano marsh past station 1 until upstream water levels rose enough (or downstream water levels fell enough) to reverse the gradient. Hydrographs for stations 1 and 36 also reflect the large storage capacity of Punamano marsh and the network of ditches that lie upstream of station 1. The finite capacity of the station 1 duckbill to release this stored water contributes to the slow recession in water level at stations 1 and 36.

Kii pond B is physically isolated from adjacent ditches by high berms, and its hydrograph (station 21, fig. 8) varies mainly in response to rainfall (which falls directly on the pond), evaporative loss, possible seepage loss, and inflow-outflow controls by USFWS. An

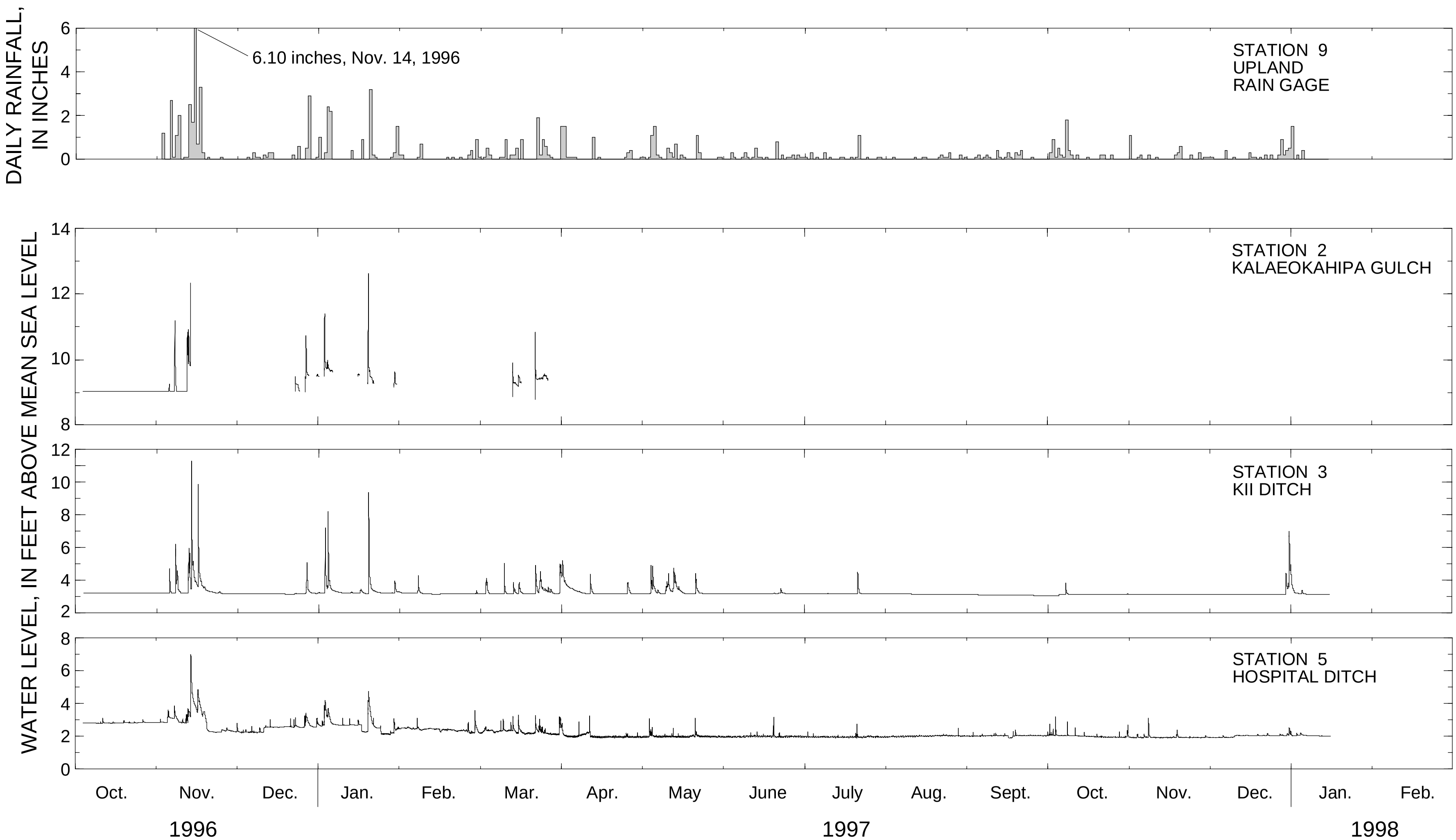


Figure 10. Water-level hydrographs for stations 2, 3, and 5 and daily rainfall at station 9, October 1996 to January 1998, James Campbell National Wildlife Refuge, Oahu, Hawaii.

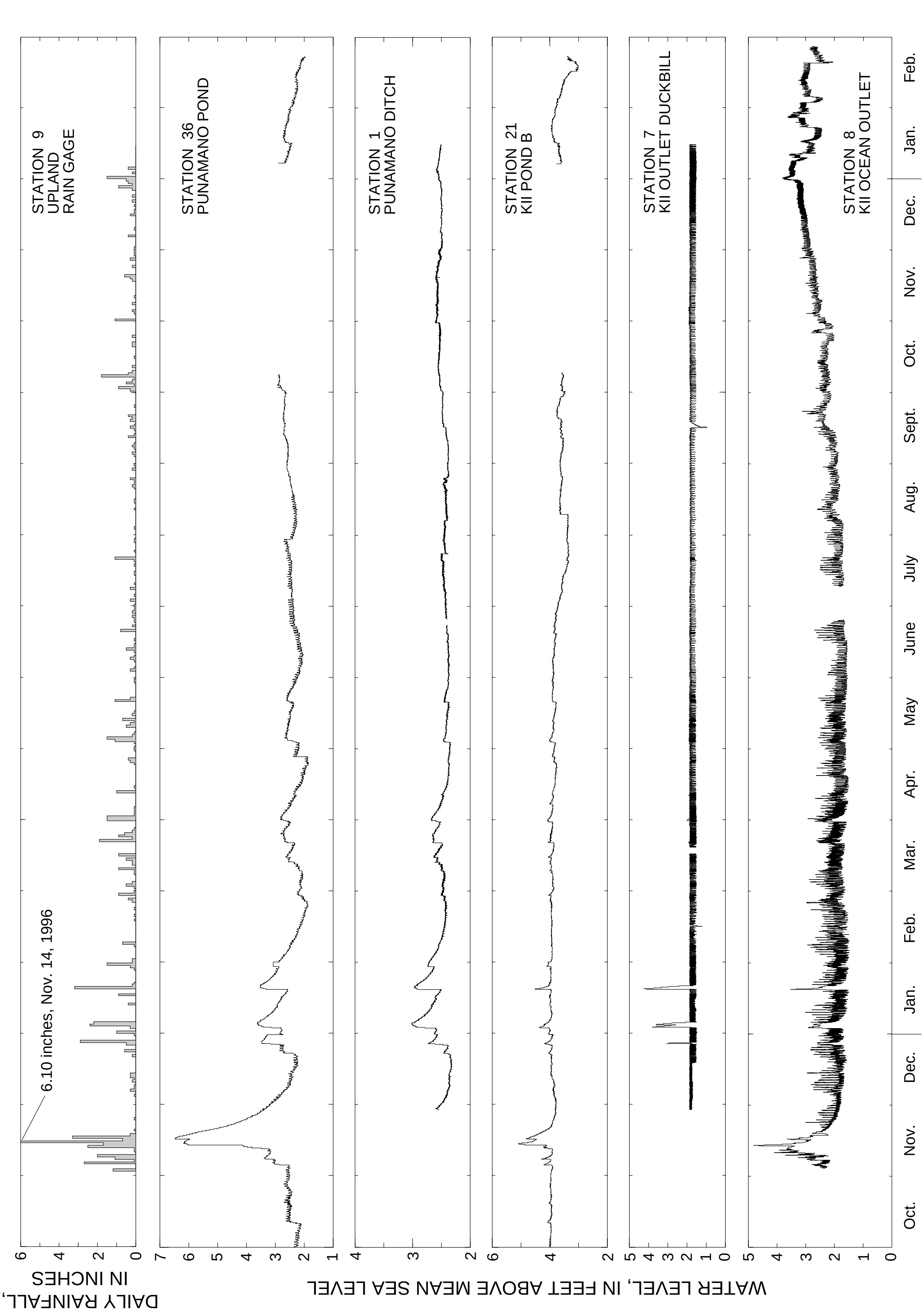


Figure 11. Water-level hydrographs for stations 1, 7, 8, 21, and 36, and daily rainfall at station 9, October 1996 to January 1998, James Campbell National Wildlife Refuge, Oahu, Hawaii.

important exception took place in November 1996: the large peak in the hydrograph indicates that stormflow in Hospital ditch flooded the pond by overtopping flashboards in the pond water-control structure (station 30). The subsequent recession in the pond B hydrograph indicates that a similar volume of water drained back out of the pond as ditch water levels declined. Other ponds at Kii Unit were similarly flooded by ditch water during this storm.

Station 7 measured the level of Punamano ditch near the Kii outlet pump. The main feature in this hydrograph (fig. 8) is the fair-weather ditch level of about 1.8 ft, which was controlled by the outlet pump being calibrated to that level. Repetitive pumping caused drawdown and recovery cycles of about 0.5 ft in the ditch. Large positive spikes in the record correspond to stormflows that forced the station 7 duckbill valve open, releasing water to the outer ditch. Two negative spikes also appear in the record, in February and September 1997. These were sustained periods of pumping that were actuated manually, overriding the automatic controls, to facilitate maintenance operations by USFWS.

The hydrograph at station 8 (fig. 8) reflects outflow from inner ditches of the Refuge, downstream restrictions imposed by the Kii ocean outlet channel, and the storage capacity of the outer ditch system and surrounding area (figs. 6 and 7). Stormwaters can overtop low berm swales in this area, effectively merging the outer ditch with Punamano, Hospital, and Raboy ditches, and inundating Kii ponds A and E and adjacent lowlands. This large volume of stored water drains slowly through the ocean outlet and fosters a slow recession in the hydrograph, even under free outflow conditions. Restrictions to outflow include the narrow width of the channel, the sand plug that builds up within the channel, and backwater resistance from the ocean. High ocean level causes backwater resistance by lessening the hydraulic gradient from the outer ditch system to the ocean. Flow even reverses in the outlet channel when ocean level is high enough, with seawater flowing back upstream into the outer ditch system. This happens at almost every high tide when the sand plug has been washed out and inland runoff is small. It can also happen when a sand plug is present, through a combination of high tides and large surf that allows waves to wash up and over the sand plug.

Runoff Volume

Principal surface-water inflows and outflows to and from the coastal plain in the vicinity of the Refuge were computed by month and year (table 4). Inflow is considered to be the total discharge from outlying gages 1 through 5 into the combined lowland ditch system that drains the coastal plain. Outflow is the total discharge at the inner ditch terminus at Kii Unit, or the sum of outflow through the station 7 duckbill valve plus pumpage through the Kii outlet pump (station 11). Owing to inadequacies in some of the stream-gaging data, discharge was estimated for some months at station 2 and for all months at station 5 by area-weighted pro-rating of station 1 discharge using drainage areas from table 1. The estimated discharge at stations 2 and 5 amount to only 1.4 and 1.1 percent, respectively, of the total inflow from outlying gages 1 through 5.

In 1997, stream gages measured 331 Mgal of inflow from outlying gages and 457 Mgal of outflow. The influence of winter stormflows is pronounced, with most of the inflow taking place in January, March, April, and May, and smaller to negligible amounts in other months. This reflects the flashy, intermittent character of the streams, which flow heavily during storms, but little or not at all during fair weather.

Ohi Ai Gulch (station 3) is the overwhelming contributor of runoff in the vicinity of the Refuge. Kalaeokahipa Gulch (station 2) is a distant second, and smaller amounts of runoff are contributed by Punamano marsh (station 1), Kahuku storm drain (station 4), and Hospital ditch (station 5). Discharge at station 3 accounted for 89 percent of the 331 Mgal of inflow from outlying gages, probably because the drainage basin for station 3 is large (58 percent of total drainage area for stations 1 through 5), extends much farther into the rainy uplands than other basins, and has steep terrain in the upland part of the basin. Notably, the November 1996 discharge of 265 Mgal at station 3 equals 90 percent of the entire year's discharge for that station in 1997, and 80 percent of the 1997 inflow from outlying gages 1 through 5, again reflecting the overwhelming role played by stormflows.

Outflow at the ditch terminus in 1997 was 457 Mgal, which is 125 Mgal greater than inflow from the outlying gages. The apparent excess in outflow (125

Table 4. Monthly discharge of streams and ditches flowing in and out of the coastal plain near James Campbell National Wildlife Refuge, Oahu, Hawaii, October 1996 through December 1997

[Values in million gallons (Mgal), except where noted in million gallons per day (Mgal/d); --, not available; e, estimated from Station 1 discharge by area-weighted pro-rating using the drainage areas in table 1; stations are shown on figure 6]

Month	Inflow at outlying stream gages						Outflow at the inner ditch terminus at Kii Unit			Inflow minus outflow[1]
	Station 1	Station 2	Station 3	Station 4	Station 5	Total	Station 7	Station 11	Total	
1996										
October	--	--	2.57	--	--	2.57	--	--	--	--
November	--	--	264.56	--	--	264.56	--	--	--	--
December	3.47	4.63	14.04	0.32	--	22.46	0.07	--	--	--
1997										
January	2.02	15.25	113.45	1.99	e1.30	134.01	7.83	149.26	157.09	-23.08
February	0.47	e1.16	4.96	0.17	e0.30	7.06	0.01	34.84	34.85	-27.79
March	1.96	3.57	32.27	0.36	e1.27	39.43	-0.05	62.28	62.23	-22.80
April	1.03	e2.55	74.48	0.24	e0.66	78.96	0.61	61.92	62.53	16.43
May	0.35	e0.87	47.47	0.12	e0.23	49.04	0.07	39.06	39.13	9.91
June	0.00	e0.00	2.75	0.01	e0.00	2.76	0.00	16.20	16.20	-13.44
July	0.01	e0.02	7.34	0.14	e0.01	7.52	0.00	12.26	12.26	-4.74
August	0.00	e0.00	1.61	0.13	e0.00	1.74	0.00	7.65	7.65	-5.91
September	0.03	e0.07	0.26	0.02	e0.02	0.40	0.00	7.99	7.99	-7.59
October	-0.02	e0.00	2.13	0.14	e0.00	2.25	0.01	11.08	11.09	-8.84
November	0.01	e0.02	1.31	0.16	e0.01	1.51	0.00	12.11	12.11	-10.60
December	-0.03	e0.00	6.72	0.06	e0.00	6.75	0.00	33.79	33.79	-27.04
1997 total (Mgal)	5.83	23.51	294.75	3.54	3.80	331.43	8.48	448.44	456.92	-125.49
1997 average (Mgal/d)	0.016	0.064	0.808	0.010	0.010	0.908	0.023	1.229	1.252	-0.344

[1] Negative values indicate that outflow exceeds inflow

[2] Discharge at Kii outlet pump was estimated as product of measured pump duration times nominal pump rating of 12,000 gallons per minute

Mgal) equates to 27 percent of the outflow and 38 percent of the inflow. Measured outflow does not include ungaged outflow that overflowed flood-relief swales at the ditch terminus during storms in January 1997. Inclusion of this outflow would make the excess outflow even (a more negative balance residual). Of the measured outflow, 98 percent was through the Kii outlet pump, with the station 7 duckbill valve only opening for brief periods during storms.

Positive residuals (more water in than out) signify net storage of water during the month, probably as bank storage along the ditch reaches between the outlying gages and the ditch terminus, and in shallow aquifers and other surficial materials. Negative residuals signify the delayed outflow of this stored water, as well as independent contributions of ground-water discharge from deeper aquifers. In this scheme, the predominance of outflow over inflow for 1997 is attributable to gains from underlying aquifers, because surface-water inflows and outflows should roughly balance over the course of a year. The month of September 1997 is particularly informative (table 4): inflows were almost negligible (0.40 Mgal) yet the Kii outlet pump (station 11) discharged 7.99 Mgal (266,000 Mgal/d), most of which must have originated as ground-water discharge.

Outflow from Punamano Unit, measured at station 1 (inflow to Kii Unit), totalled 5.83 Mgal during 1997. The small negative discharge values in October and December (table 4) may simply be instrument noise resulting from low flow velocities that approach the precision and resolution of the flow meter, or they may indicate small amounts of backflow through the station 1 duckbill valve, which may not close entirely or may be held slightly open by small obstructions such as plant debris.

Observations Related to Stormflows and Flooding

The lowlands of the Kahuku area flood frequently. The most severe flood in recent times occurred in March 1991 and caused extensive damage in the town of Kahuku.Much of the coastal lowlands seaward of Kamehameha Highway were inundated, and farms and aquafarms were damaged. Flooding of the Refuge disrupted endangered waterbird nesting and maintenance habitat, and caused the loss of nests and young. A key factor in the March 1991 flooding may simply have been the magnitude of the storm: the maximum 24-hour rainfall at Kahuku during the 2-day period March 19–20, 1991 was 17.4 inches, corresponding to a recurrence interval in excess of 100 years in terms of rainfall (State of Hawaii Department of Land and Natural Resources, 1984; 1991).

Reports attributed flooding to inadequate capacity of existing channels and ocean outlets, and to water ponding in low areas both inland and seaward of the highway (Kahuku Flood Relief Task Force Committee, 1991; State of Hawaii Department of Land and Natural Resources, 1993; R.M. Towill Corporation, 1997). These reports also called for future flood mitigation through the re-opening of lowland drainage ditches, more frequent clearing of vegetation from existing channels, and new drainage projects such as bridge widening and creation of new flood channels.

Stream-stage and discharge data collected during this study provide insight into some of the factors that govern storm runoff to and from the Kahuku coastal plain. The scope of our investigation did not include an exhaustive study of flooding, therefore many questions will be left unanswered in the following discussions. Also, the spatial coverage of gaging stations in this study necessarily restricts insight to areas including and immediately surrounding the James Campbell National Wildlife Refuge.

Storms

Data for three large storms were included in the surface-water records collected during this study. Peak flood stages, discharges, and times-to-peak data are summarized in table 5 for the storms of November 14, 1996, January 3, 1997, and January 19, 1997.

The largest storm during the study period was on November 14, 1996. Heavy rains were produced by a particularly stable low-pressure system that was anchored by a long-wave trough that directed deep tropical moisture to Hawaii in a southwesterly flow (known as a Kona low in Hawaii). The upland rain gage at station 9 registered 6.1 inches of rain for the day, most of which fell in the first 2 hours after midnight. The maximum hourly rainfall was 3.6 inches, with high-intensity rain starting at 0045 hours and continuing through 0130 hours. Rainfall-frequency maps for Oahu (State of Hawaii Department of Land and Natural Resources, 1984) indicate that the maximum 1-hour rainfall corresponded to a 50-year recurrence interval, but the 24-hour rainfall corresponded to only a 2-year recurrence interval. Thus the November 14 storm was intense, but brief, in terms of rainfall.

Peak flood stages recorded during the November 1996 storm were the highest of the study period at the gages that were operational before the event. Peak discharges (table 5) were 910 and 1,020 ft^3/s at stations 2 and 3. These peak discharges were determined by applying the slope-area method (Fulford, 1994) to data collected at the stations. A comparison to flood-frequency data (Wong, 1994) and November 1996 peak discharge data available for two continuous-record gages operated by the USGS on nearby Kamananui Stream (Hill and others, 1998) indicate that this flood had a recurrence interval of about 3 to 4 years. A daily discharge of 114 Mgal for November 14, 1996 was computed for station 3 from its continuous stage record. A daily discharge was not computed for station 2 because the gage was washed away in the early part of the storm.

Flow went overbank at several points in the streams and ditches during the November 1996 storm. The most conspicuous out-of-channel flow was at Kalaeokahipa Gulch at Kamehameha Highway. The stream had gone overbank upstream of the highway, with most of the flow being returned to the main channel by drainage swales running along the highway. Flow exceeded the capacity of the rectangular bridge opening beneath the highway, running over the highway and blanketing it with a layer of alluvial silt. The capacity of the bridge opening during the flood was reduced to some degree by woody debris, some of which remained plastered on the upstream face of the bridge after the storm. Most of the over-highway flow re-entered the channel just downstream of the highway, washing station 2 away in the process. The 12-ft long stilling well and attached instrument shelter were found

Table 5. Peak stage, discharge, and time to peak stage at surface-water gaging stations during storms in November 1996 and January 1997, James Campbell National Wildlife Refuge, Oahu, Hawaii

[Peak stage in feet above mean sea level; stages are from continuous recorders except where noted in remarks column; ft, feet; ft^3/s, cubic feet per second; hr, hour; min, minute; e, estimated; <, actual value is thought to be less than the value shown; >, actual value is thought to be greater than the value shown; --, not measured, not applicable, or none; stations are shown on figure 6]

Station number	Maximum during storm of November 14, 1996			Maximum during storm of January 3, 1997			Maximum during storm of January 19, 1997			Remarks
	Stage (ft)	Discharge (ft^3/s)	Time to peak[1] (hr, min)	Stage (ft)	Discharge (ft^3/s)	Time to peak[2] (hr, min)	Stage (ft)	Discharge (ft^3/s)	Time to peak[3] (hr, min)	
36	6.2	--	18 hr, 34 min	3.5	--	19 hr, 21 min	3.5	--	22 hr, 06 min	January 3 peak somewhat obscured by additional rain on January 4
1	--	--	--	2.9	8.7	19 hr, 25 min	3.0	7.8	24 hr, 05 min	January 3 peak somewhat obscured by additional rain on January 4
2	18e	910	>0 hr, 30 min	11.4	42	1 hr, 15 min	12.6	84	1 hr, 15 min	November 14 peak from surveyed high-water mark, and time to peak is when gage washed out
3	11.9	1,020	1 hr, 30 min	7.2	270	1 hr, 45 min	9.4	600	1 hr, 45 min	November 14 peak from surveyed high-water mark; higher peak on January 4 after additional rain
4	--	--	--	4.4	24	4 hr, 35 min	5.0	40	3 hr, 35 min	--
5	7.0	--	2 hr, 30 min	4.2	--	4 hr, 15 min	4.8	--	3 hr, 15 min	--
7	--	--	--	3.8	7.2	3 hr, 25 min	4.2	9.0	3 hr, 55 min	--
8	4.8	--	4 hr, 45 min	2.9	--	5 hr, 35 min	3.5	--	4 hr, 25 min	--
11	<6e	--	--	4.0	27	3 hr, 24 min	4.3	27	3 hr, 35 min	November 14 peak estimated as lower than surveyed altitude of pumphouse floor, which was not inundated
21	5.1	--	16 hr, 0 min	--	--	--	--	--	--	Pond B flooded by Hospital ditch on November 14
33	--	--	--	4e	--	--	--	--	--	Observed Punamano ditch about 0.7 ft higher than inner swale and flowing upstream into Hospital ditch
34	--	--	--	4e	--	—	--	--	--	Observed Punamano ditch about 0.3 ft higher than outer swale and flowing to outer ditch, which was about 0.7 ft lower than swale

[1] As measured from start of intense rain November 14 at 0045 hours at station 9 upland rain gage

[2] As measured from start of intense rain January 3 at 1015 hours at station 9 upland rain gage

[3] As measured from start of intense rain January 19 at 2015 hours at station 9 upland rain gage

more than a mile downstream in Punamano ditch. Data were retrieved from the recorder and the last recorded steam stage was 12.3 ft (3.3 ft water depth in channel) at 0115 hours. The peak stage at the original location of station 2 was estimated from high-water marks to be about 18 ft (9 ft water depth in channel).

The station 2 stilling well and instrument shelter came to rest in Punamano ditch, upstream (west) of its confluence with Kalaeokahipa Gulch, indicating upstream movement of water in Punamano ditch at this location. This upstream flow was confirmed by the characteristics of the silt layer deposited across Nudist Camp Road at the future site of station 1. In addition to crossing the road, Punamano ditch also went overbank east of station 1, flooding adjacent ranchland in the seaward direction. The peak stage at Punamano pond station 36 during the November storm was 6.2 ft and the altitude of Nudist Camp Road is about 6 ft.

At Kii ditch, November flow was bankfull or very slightly overbank along the reach of ditch seaward of Kamehameha Highway past station 3, where the flood peak of 11.9 ft equalled 8.2 ft water depth in the channel. Hydraulic analysis using surveyed high-water marks and stream cross sections indicates that the bankfull flow at Kii ditch resulted simply from magnitude of the discharge and that stage at this location was not affected by backwater (R.A. Fontaine, USGS, oral commun., 1998). Stormwater in Kii ditch also crossed the access road to the Kii Unit, where the ditch and road make a 90-degree turn to the west by the sewage treatment plant. The overflow entered an inactive ditch bordering a banana farm to the east of Kii ditch.

At Hospital ditch near station 5, a thin and narrow blanket of silt across Kamehameha Highway indicated that the bridge crossing was just slightly overtopped in the November storm. The peak stage of 7 ft at station 5 (table 5) is essentially the same as the highway altitude there. At station 8, the peak stage of 4.8 ft indicates that the flood-relief swale separating inner and outer ditches (station 34, altitude 3.5 ft) was inundated during the November storm. This is corroborated by water levels in the Kii ponds, because most were flooded by the ditches. At Kii pond B (station 21), the hydrograph and peak stage of 5.1 ft (fig. 11 and table 5) confirm pond B was flooded, probably by Hospital ditch overtopping flashboards in the water-control structure (station 30). Manual staff-gage readings (M. Silbernagle, USFWS Haleiwa office, written commun., 1999) suggest that other Kii ponds also were flooded by ditch waters: pond A, 4.54 ft; pond C, 5.07 ft; pond D, 5.08 ft; pond E, 5.00 ft; pond G, 5.06 ft. Taken together, the pond water levels imply peak stage of about 5.1 ft at the inner ditch terminus. Given the 0.3 ft drop in head from there to station 8, water would have been flowing freely across the swale from inner to outer ditch.

The storms of January 3 and 19, 1997 were of a lesser magnitude than the November 1996 storm but were documented more completely in that most of the gaging stations installed for this study were operational then. The upland rain gage at station 9 registered 2.4 inches of rain on January 3. The maximum hourly rainfall was 1.0 inches and the highest intensity rain started at 1015 hours. On January 19 station 9 registered 3.4 inches of rain. The maximum hourly rainfall was 1.6 inches and the highest intensity rain started at 2015 hours.

Peak flood stages in January were lower than November peak stages at all stations. January peak stages at stations 2 and 3 corresponded to half-bankfull flow. Similarly, peak discharges in January were smaller than in November at stations 2 and 3 (table 5). The outlet pump at station 11 operated continuously for periods from one to several days during the January storms, however it was not able to discharge sufficient water to keep the ditches from topping the flood relief swales at stations 33 and 34. This is clear from looking at the peak stages at stations 7 and 11 for the January storms, which were both higher than the altitudes of the ditch swales. Peak stage in the Kii outlet channel at station 8 reached 2.9 ft on January 3 and 3.5 ft on January 20. Peak stages at Punamano north pond were 3.5 ft for both January storms while peaks at station 1 were 2.9 ft on January 3 and 3.0 ft on January 20.

Stream Response Times and Stream Gradients

During the storms of November 1996 and January 1997, streams and ditches at the various gaging stations showed a broad range in the timing of runoff (table 5) and in the character of the stream hydrographs (figs. 12–14). Upland stations 2 and 3 had the quickest responses, with times-to-peak-stage of less than 2 hours from onset of intense rain. Stations 4, 5, 7, and 8 had slightly slower responses in the 2 to 6 hour range. Stations 1 and 36 had the longest and most variable times-to-peak, ranging from 18 to 24 hours.

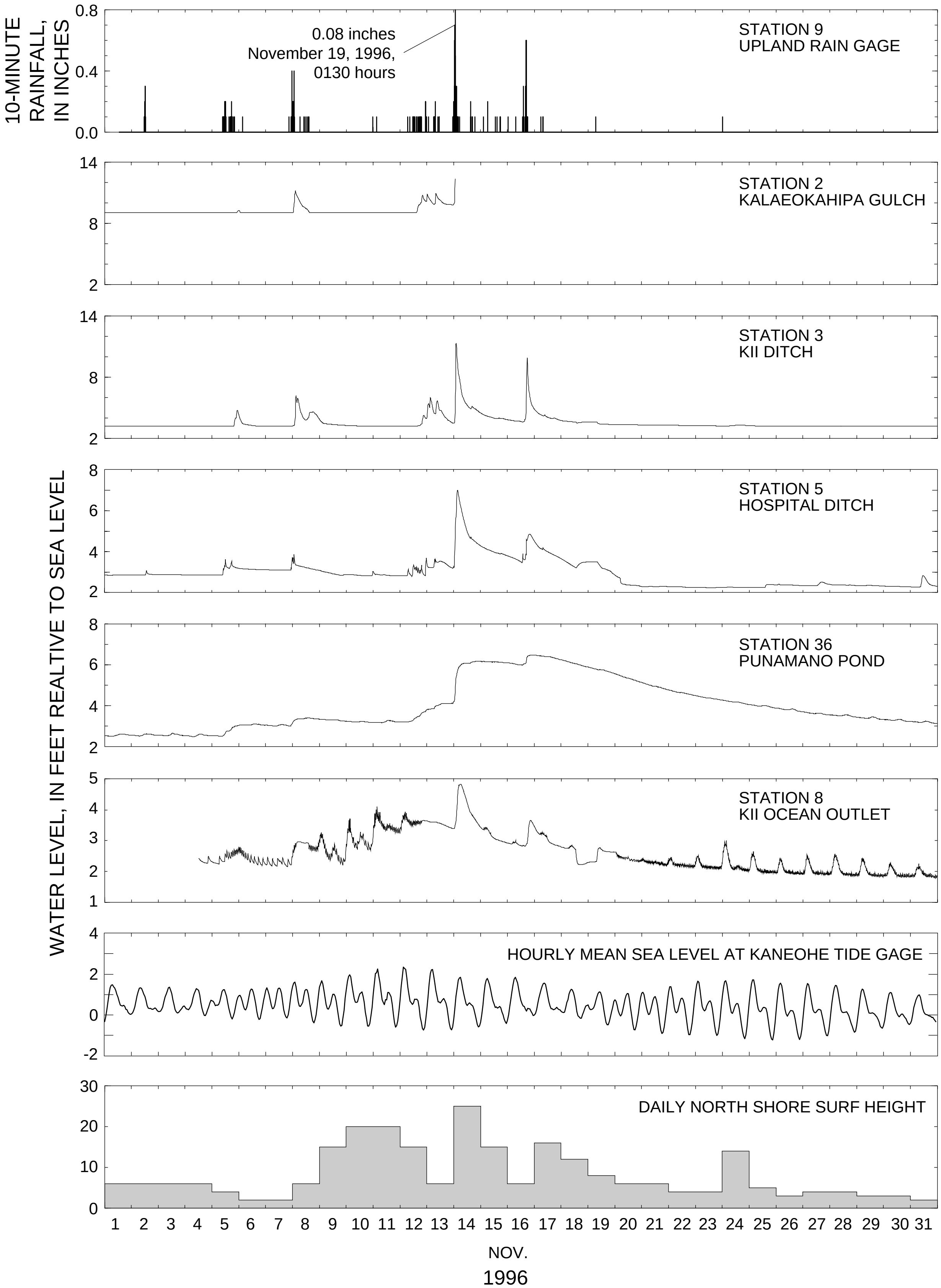


Figure 12. Water-level hydrographs at stations 2, 3, 5, 8, and 36, and 10-minute rainfall at station 9, November 1996, James Campbell National Wildlife Refuge, Oahu, Hawaii. Also shown are hourly mean sea level at Kaneohe tide gage (mean of hourly values from the National Oceanic and Atmospheric Administration, accessed March 20, 1998 by telnet at wlnet2.nos.noaa.gov), and daily North Shore surf height (P. Caldwell, National Oceanic and Atmospheric Administration, written commun., 1998).

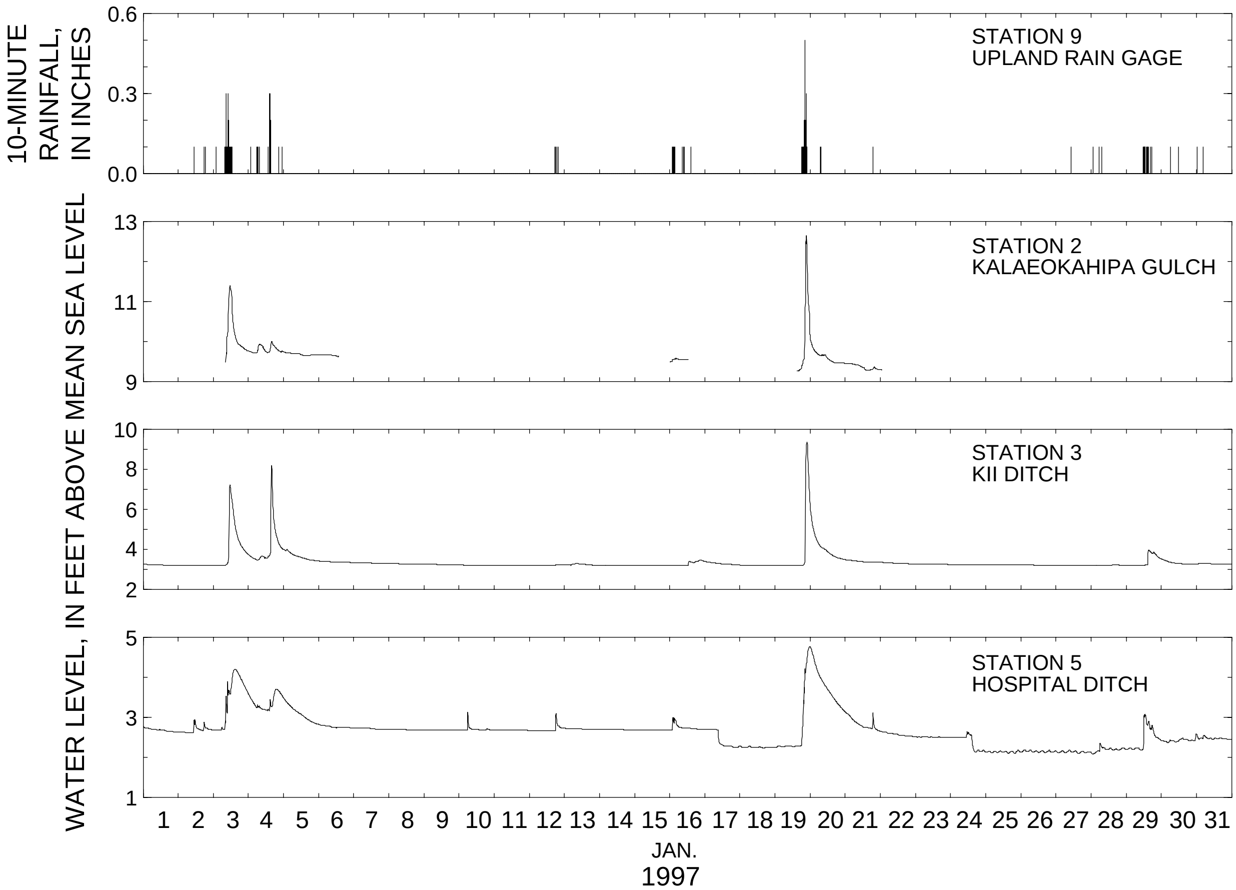


Figure 13. Water-level hydrographs for stations 2, 3, and 5 and 10-minute rainfall at station 9, January 1997, James Campbell National Wildlife Refuge, Oahu, Hawaii.

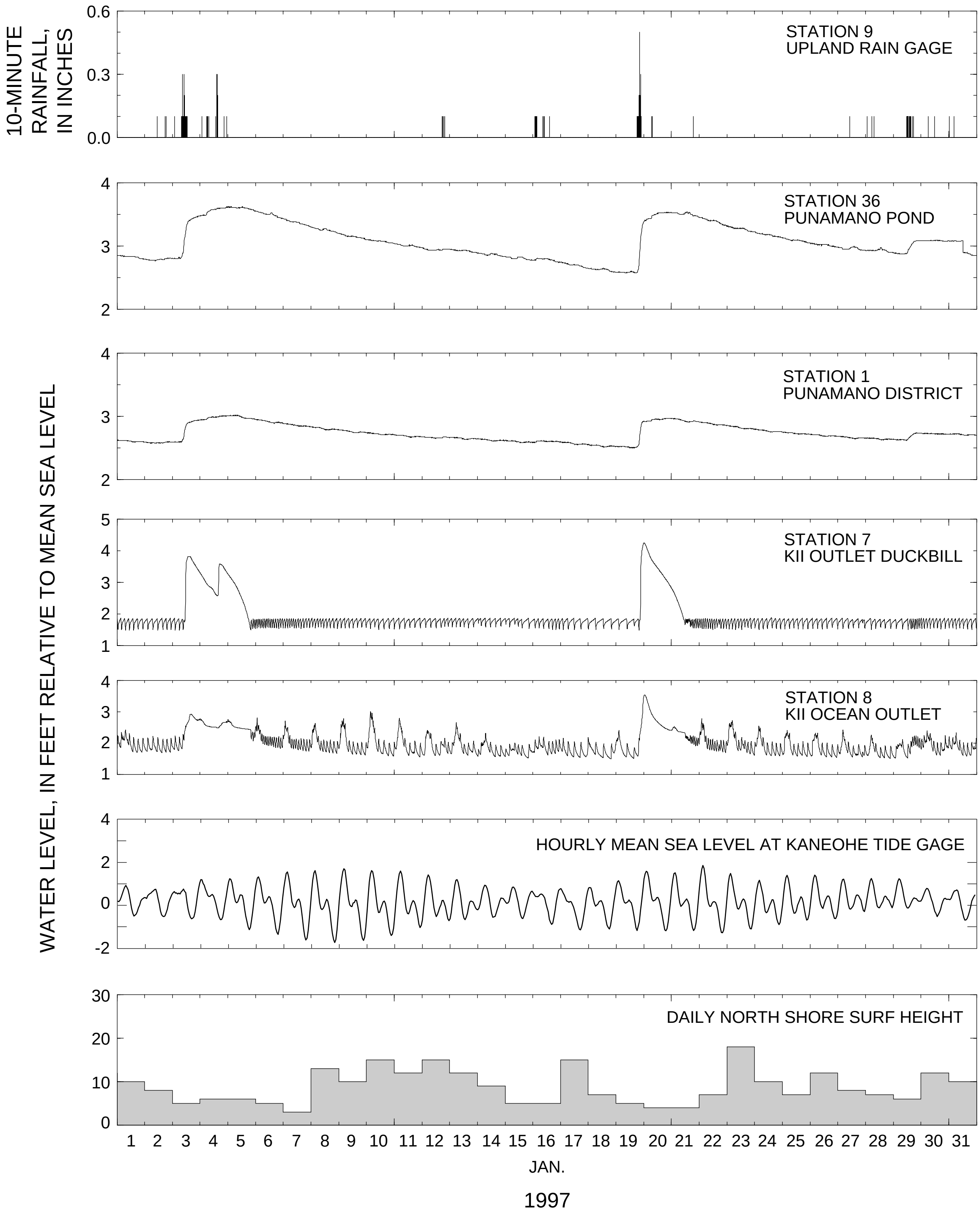


Figure 14. Water-level hydrographs for stations 1, 7, 8, and 36, and 10-minute rainfall at station 9, January 1997, James Campbell National Wildlife Refuge, Oahu, Hawaii. Also shown are hourly mean sea level at Kaneohe tide gage (the National Oceanic and Atmospheric Administration, accessed March 20, 1998 by telnet at wlnet2.nos.noaa.gov), and daily North Shore surf height (P. Caldwell, National Oceanic and Atmospheric Administration, written commun., 1998).

The rapidity with which water will be conveyed downstream and out to sea from any point depends largely on stream gradient. The hydraulic head drop and average gradient from each gaging station (at the time of its peak stage) to Kii inner ditch terminus station 7 and Kii ocean outlet station 8 are shown in tables 6 and 7. Analyses of stream gradients are useful for considering where potential backwater effects may be significant.

Using the January 3 storm values in table 6 as an example, the largest gradients were from upland stations with the highest peak stages: station 2 at Kalaeokahipa Gulch (7.1 ft/mi) and station 3 at Kii ditch (5.1 ft/mi). In contrast, the gradient from station 5 at Hospital ditch was 0.5 ft/mi and from station 36 at Punamano north pond it was only 0.1 ft/mi. The gradient from station 1 at Punamano ditch was negative, -0.4 ft/mi, indicating that the water level at station 7 was higher than at station 1 and that the station 1 duckbill valve was closed. The gradient from station 8 at Kii ocean outlet was -3.8 ft, corresponding to a -0.9 ft head drop from the inner ditch to the outer ditch (station 7 to station 8). Similar relations among stream gradients were observed during the November 14 and January 19 storms, and when gradients were referenced to station 8 (table 7) rather than to station 7 (table 6).

Stream gradient is one of the factors that affect the timing of runoff, particularly on stream recession. Upland stations 2 and 3 have the steepest gradients and quickest recessions whereas stations 1 and 36 have the smallest gradients and slowest recessions, lasting tens of days (figs. 12–14). Other stations are intermediate between these extremes.

Sea-Level Interactions and Potential Backwater Effects in Lowland Areas

Stream gradients are gentle in the Punamano and Kii Units of the Refuge and the lands along Punamano and Hospital ditches. As a result, streamflow and flood conditions are sensitive to any downstream restrictions and resulting backwater effects. This topic is best discussed starting from the downstream end of the system and working upstream.

Kii ocean outlet is the most downstream point in the drainage network of the Kahuku coastal plain and is important in regulating outflow from the plain. The outlet channel is narrow and a sand plug, or berm, tends to build up in the channel (fig. 3). The plug varies in height and lateral position in response to two main competing stresses: (1) high surf, which favors sand deposition, building of the sand plug, and therefore closure of the outlet channel; and (2) high ditch flows, which breach and wash out the sand plug (the plug is also cleared occasionally by the USFWS using a bulldozer or backhoe). During periods of low to medium ditchflow, water level in the Kii outer ditch system is controlled by the height of the sand plug in the outlet channel. When the plug is high, water will pond to greater height in the outer ditch. In addition to being controlled by the height of the sand plug, the outer ditch also is influenced by the ocean in two principal ways: (1) there can be backflow of seawater up the outlet channel during high tides, directly when the channel is clear and by wave overwash when a sand plug is in place; and (2) high ocean levels can impose a marine backwater influence by lessening the hydraulic gradient from the outlet channel to the ocean, hence lessening outflow velocity and discharge.

The hydrographs in figure 15 show events at and near the outlet during the 16-month period November 1996 through February 1998. The hydrographs show: (1) hourly sea level at the Kaneohe tide gage; (2) daily surf height on the North Shore of Oahu (the northwest-facing coast to the west of Kuilima Point); (3) station 8 outer ditch level near Kii ocean outlet channel; (4) station 7 inner ditch level at the terminus of Punamano and Hospital ditches (near Kii outlet pump); and (5) station 3 stream stage at Kii ditch (a good indicator of upland runoff).

A prominent trend in figure 15 is an apparent season-long episode of sand-plug buildup (indicated by a progressive increase in station 8 water level), beginning with the first high surf of the season in September 1997 and peaking in January 1998. Abrupt declines and increases in station 8 water level in January and February 1998 indicate sand-plug washouts and clearings by USFWS, alternating with subsequent rebuilding of the plug by high surf. Also evident is the varying interplay of ocean tides and pumping cycles at station 11 in causing cyclicity in the station 8 record at daily and shorter periods. Tidal range is greatest and high tides are highest during spring tides, which occur twice a month at full moon and new moon (for example, the several 14-day spring-neap tidal cycles in December 1996). Pumping cycles at Kii outlet pump (station 11) produce a mirror-image pattern in stage at stations 7 and 8: drawdown troughs at station 7 correspond to spiky peaks at

Table 6. Flood peaks, hydraulic head drop, and average gradient from stations to inner ditch terminus station 7 at Kii Unit during storms in January 1997, James Campbell National Wildlife Refuge, Oahu, Hawaii

[Stages in feet above mean sea level; ft, feet; mi, mile; ft/mi, feet per mile; station 7 is at the inner ditch terminus at Kii Unit; e, estimated; station 7 stage is at the peak time for each station; head drop is the instantaneous difference in stage from each gaging station to station 7, at the peak time; >, actual value is greater than value shown; --, not measured or not applicable; stations shown in figure 6]

Station	Distance from station 7 (mi)	Peak stage (ft)	Corresponding station 7 stage (ft)	Head drop (ft)	Average gradient (ft/mi)
		Storm of January 3, 1997[1]			
36	1.76	3.5	3.4	0.1	0.1
1	0.97	2.9	3.3	-0.4	-0.4
2	1.19	11.4	2.9	8.5	7.1
3	0.94	7.2	2.4	4.8	5.1
4	0.79	4.4	3.8	0.6	0.8
5	0.78	4.2	3.8	0.4	0.5
7	--	3.8	3.8	--	--
8	0.24	2.9	3.8	-0.9	-3.8
11	0.06	4.0	3.8	0.2	--
		Storm of January 19, 1997[2]			
36	1.76	3.5	3.1	0.4	0.2
1	0.97	3.0	3.0	0.0	0.0
2	1.19	12.6	3.5	9.1	7.6
3	0.94	9.4	3.8	5.6	6.0
4	0.79	5.0	4.2	0.8	1.0
5	0.78	4.8	4.2	0.6	0.8
7	--	4.2	4.2	--	--
8	0.24	3.5	4.2	-0.7	-2.9
11	0.06	4.3	4.2	0.1	--

[1] Station 7 pre-storm stage was 1.8 ft

[2] Station 7 pre-storm stage was 2.5 ft

Table 7. Flood peaks, hydraulic head drop, and average gradient from respective stations to Kii ocean outlet station 8 during storms in November 1996 and January 1997, James Campbell National Wildlife Refuge, Oahu, Hawaii

[Stages in feet above mean sea level; corresponding station 8 stage is the stage there at the peak time for each upstream station; head drop is the instantaneous difference in stage from each gaging station to station 8 at the peak time for the upstream station; mi, miles; ft, feet; ft/mi, feet per mile; e, estimated; --, not measured or not applicable; stations shown in figure 6]

Station	Distance from station 8 (mi)	Peak stage (ft)	Corresponding station 8 stage (ft)	Head drop (ft)	Average gradient (ft/mi)
Storm of November 14, 1996[1]					
36	1.94	6.2	3.7	2.5	1.3
2	1.37	e18	3.5	14.5	10.6
3	1.12	11.9	3.7	8.2	7.3
5	0.89	7.0	4.3	2.7	3.0
8	--	4.8	4.8	--	--
Storm of January 3, 1997[2]					
36	1.94	3.5	2.8	0.7	0.4
1	1.15	2.9	2.8	0.1	0.1
2	1.37	11.4	2.6	8.8	6.4
3	1.12	7.2	2.5	4.7	4.2
4	0.91	4.4	2.8	1.6	1.8
5	0.89	4.2	2.8	1.4	1.6
7	0.24	3.8	2.8	1.0	4.2
8	--	2.9	2.9	--	--
11	0.22	4.0	2.7	1.3	5.9
Storm of January 19, 1997[3]					
36	1.94	3.5	2.5	1.0	0.5
1	1.15	3.0	2.4	0.6	0.5
2	1.37	12.6	2.5	10.1	7.4
3	1.12	9.4	2.6	6.8	6.1
4	0.91	5.0	3.4	1.6	1.8
5	0.89	4.8	3.3	1.5	1.7
7	0.24	4.2	3.5	0.7	2.9
8	--	3.5	3.5	--	--
11	0.22	4.3	3.4	0.9	4.1

[1] Station 8 pre-storm stage was 3.4 ft

[2] Station 8 pre-storm stage was 2.1 ft

[3] Station 8 pre-storm stage was 2.1 ft

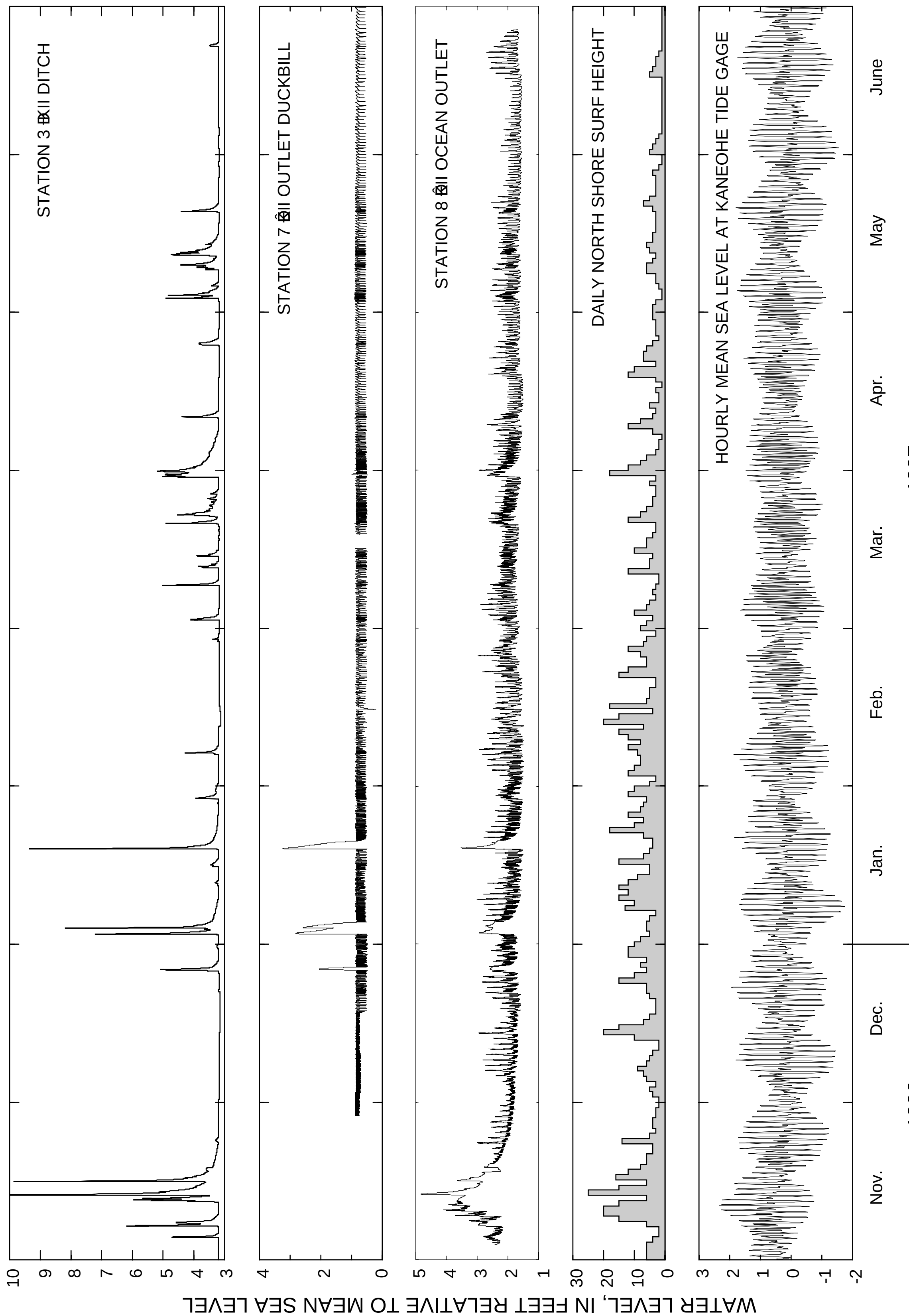


Figure 15. Stream, ocean, and pumping influences on Kii ocean outlet for the 16-month period November 1996 to February 1998, James Campbell National Wildlife Refuge, Oahu, Hawaii. Shown are water-level hydrographs for stations 3, 7, and 8, hourly mean sea level at Kaneohe tide gage (National Oceanic and Atmospheric Administration, accessed March 20, 1998 by telnet at wlnet2.nos.noaa.gov), and daily North Shore surf height (P. Caldwell, National Oceanic and Atmospheric Administration, written commun., 1998).

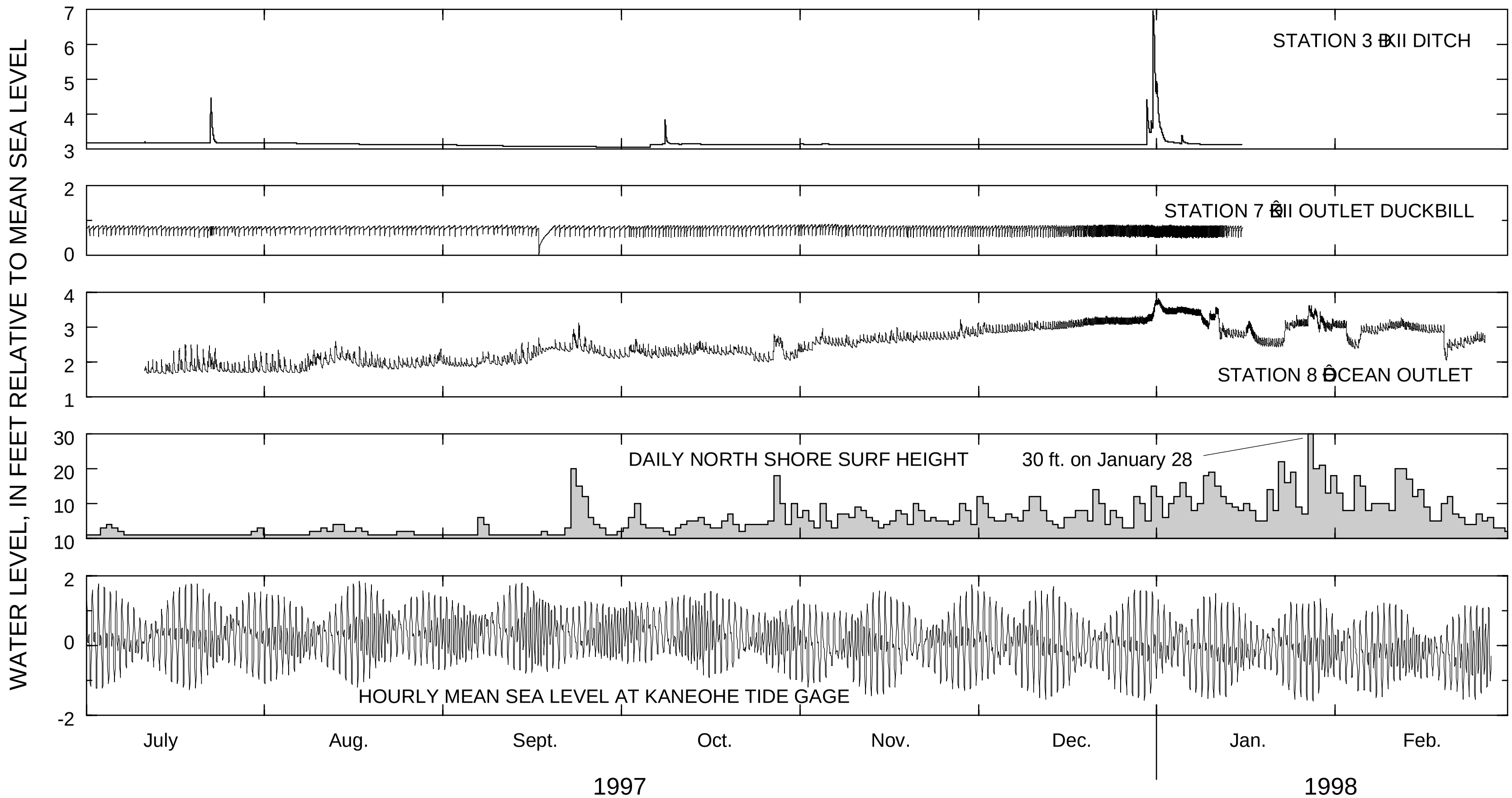


Figure 15. Stream, ocean, and pumping influences on Kii ocean outlet for the 16-month period November 1996 to February 1998, James Campbell National Wildlife Refuge, Oahu, Hawaii. Shown are water-level hydrographs for stations 3, 7, and 8, hourly mean sea level at Kaneohe tide gage (National Oceanic and Atmospheric Administration, accessed March 20, 1998 by telnet at wlnet2.nos.noaa.gov), and daily North Shore surf height (P. Caldwell, National Oceanic and Atmospheric Administration, written commun., 1998)--*Continued*.

station 8 as the Kii outlet pump transfers water from the inner to outer ditch. Pumping cycles are clearly seen in April 1997, with some high-tide influence superimposed. The length of time between pumping periods shortens dramatically when the Kii outlet pump must transfer stormwaters to the outer ditch, and pumping cycles disappeared entirely in the station 7 and 8 hydrographs for several days during the storms of November 1996 and January 1997, indicating that the pump was operating continuously. Pumping cycles were closely spaced in December 1997 and January 1998, when the outer ditch level was high. Wave washover of the sand plug during high surf is evident on September 23 and October 28, 1997. Except for these two events, the sand plug appears to have been high enough from late September through December 1997 to prevent high-tide overwash of the plug (there is a general absence of high-tide peaks in the station 8 hydrograph during this period).

During the entire 16-month period, the water level at Kii ocean outlet station 8 never dropped below 1.48 ft above sea level. Furthermore, high-tide peaks are evident in the record but low-tide troughs in the water level are not symmetrically commensurate: the record is flat-floored, as if the bottom half of the tidal cycle were blocked from having any influence. Factors that may contribute to this include: the outlet channel has a hard limestone or beachrock bottom that may act as a weir; if so its altitude may be about 1.48 ft; the outer ditch system just inland of the outlet channel is lined with mud that may inhibit infiltration and fall of outer ditch level below some minimum limit; the shallow ground-water table in the vicinity may act as a lower limit.

Some of the processes discussed above are more distinguishable in hydrographs with expanded time scales (figs. 12–14). The pronounced peaks in the station 8 hydrograph at daily frequency are high-tide episodes of wave overwash or direct seawater backflow up the ocean outlet channel (clearly identifiable in fig. 12, November 9–12 and November 24–December 1, and throughout most of fig. 14). The highest-frequency "noise" in the station 8 hydrograph, with periods on the order of hours or less, reflects cyclic pumping by the Kii outlet pump (seen most clearly in fig. 14 on January 1–2 and 15–18). Pumping-cycle noise is absent in the station 8 hydrograph from late evening November 12 through November 19 (fig. 12) and in both stations 7 and 8 hydrographs during the January flood peaks (fig. 14). This signifies that the outlet pump was not cycling during these periods, but instead was operating continuously in an attempt to transfer floodwaters from inner to outer ditch.

Events surrounding the November 14 storm (fig. 12) at the ocean outlet are significant because they illustrate several key factors affecting drainage at the outlet. A gradual rise in station 8 ditch level from November 9 to 12 corresponds to a 4-day period of high surf. This could represent either a gradual buildup of the sand plug in the outlet channel or progressively higher ocean levels resulting from "wave setup," a super-elevation of local sea level by waves piling up at the shore. The gradual rise in station 8 stage over this 4-day period is punctuated by high-tide peaks of wave overwash or seawater backflow in the channel. The station 8 hydrograph shows rapid pump cycling on November 5–6 and on November 8–12 in response to the small rainstorms on November 5, 8, and 12–13. The absence of cycling on November 8 indicates that the outlet pump was operating continuously to dispose of stormwater. The pump also operated continuously from late evening November 12 through November 13, with no rise in station 8 stage (actually, there was a 0.26-ft drop during this period). The fact that the pump was transferring water into the outer ditch at a rate of 12,000 gal/min (17.2 Mgal/d) with no rise in outer ditch stage suggests that the sand plug had been washed out by this continual flow, or that the pump was recirculating outer-ditch water that was flowing inward over the outer flood-relief swale. If a sand plug were still present just before the November 14 storm peak, it would have washed out early in the storm and would not have been present at the times of the flood peaks at the inland gaging stations. Following the November 14 storm peak, station 8 stage declined gradually to about 1.6 ft by the end of November, with the outlet pump operating continuously through November 19 and cycling rapidly thereafter. Notably, the November 14 storm coincided with the highest surf of the month (25 ft) and occurred about 2 days after spring tide. Thus, the high outer ditch levels before and during the November 14 storm were probably caused by remnant stormwater from small rainstorms earlier in the month and a marine backwater effect from high ocean levels that hindered outflow. The high ocean levels were due to the coincidence of spring high tides and wave setup from large surf.

Whether high levels in the ocean and outer ditch contributed to backwater effects farther upstream in November 1996 is difficult to determine. Station 7 definitely did not experience a backwater effect from the outer ditch during the January storms. Peak stage was 0.7 to 1.0 ft higher in the inner ditch at station 7 than at station 8 (table 7), resulting in a hydraulic step-down over the outer flood-relief swale. But on November 14, the pre-storm stage in the outer ditch at station 8 was 3.4 ft, compared with 2.1 ft for the January storms (see footnotes, table 7). Thus, the inner ditches were working against an additional 1.3 ft of water in conveying runoff out of the coastal plain during the November 14 storm. This may have contributed to backwater effects at station 7 and points farther upstream. The outer ditch level peaked at 4.8 ft during the November storm and the inner ditch level peaked at about 5.1 ft (stations 8 and 21, table 5). Presuming that these peaks were coincident in time, the small head drop of 0.3 ft from the inner ditch to station 8 makes it difficult to judge whether the head drop represents a hydraulic step-down over the outer flood-relief swale; a gradient corresponding to free, unhindered outflow; or a gradient reflecting backwater influence. To discriminate among these possibilities would require detailed hydraulic modeling and analysis that are beyond the scope of this study.

A backwater effect was evident at station 1 in both January storms. Table 6 shows that at the time-of-peak at station 1, the stage at station 7 downstream was either higher than or equal to station 1 stage, and that the gradient between the two stations was flat (January 19) or even negative (January 3). Figure 14 shows that the head disparity was even greater at earlier times, prior to the station 1 time-of-peak when station 7 stage was higher. In fact, the stage at station 7 was a full foot higher than at station 1 early on January 20. During periods of backwater at station 1, the duckbill valve closes and no discharge occurs. Therefore, water goes into storage in Punamano marsh, raising water levels there (see station 36, fig. 14). In the January storms, this stored water began to drain only when stage at station 7 had declined sufficiently to allow the station 1 duckbill valve to reopen, typically a day or two after the start of the storm. The November 1996 storm caused a more extreme backwater effect on Punamano marsh, when floodwaters in Punamano ditch overtopped Nudist Camp Road and flowed back upstream into the marsh. This phenomenon has water-quality implications for Punamano Unit in that the floodwaters would transport high concentrations of suspended sediment to the marsh and potentially other contaminants such as nutrients, pesticides, and volatile organic compounds.

The low altitude of Hospital ditch at Kamehameha Highway may subject it to backwater effects from farther downstream. Stations 4 and 5 were not subjected to fully flat backwater conditions in January (table 6 and fig. 13). However, the magnitude of head drop to station 7 during the January storms was small (only 0.4 to 0.8 ft) and the times-to-peak at stations 4 and 5 strongly indicate backwater as having an effect (that is, they are nearly the same as at stations 7 and 11, instead of the much shorter times that could be expected from such small watersheds). Thus, the times-to-peak-stage at stations 4 and 5 may reflect the backing-up of water in Hospital ditch more than the actual peak flows being conveyed down their drainages. Field observations were made at the flood-relief swales at the inner ditch terminus on January 3, and backflow was noted at the inner swale (station 33), with water flowing from Punamano ditch back upstream into Hospital ditch (see remark for station 33, table 5). This likely reflects the overwhelming contribution of runoff to Punamano ditch from Ohia Ai and Kalaeokahipa Gulches owing to their larger watersheds. Such backflow will cause a backwater effect in Hospital ditch, possibly as far upstream as Kamehameha Highway, and could contribute to localized flooding there. The risk for flooding would be greatest if high downstream water levels coincided with peak flows coming down the Hospital ditch drainage. Backwater is not likely to have played a role in the slight flooding of Hospital ditch at Kamehameha Highway during the November 14 storm. The flooding across the highway appeared to result from blockage or exceedance of culvert capacity at the upstream side of the highway. Downstream of the highway, head dropped 2.2 ft from station 5 to station 8 (table 7), equalling a gradient of 3.0 ft/mi. This is greater than the gradient of the stream channel, and likely corresponds to free drainage, unimpeded by backwater.

At upland stations 2 and 3, it is unlikely that backwater effects existed during the November or January storms. Head drop from these stations to downstream stations 7 and 8 exceeded 4 ft for all storms and stream gradients were the steepest of all the stations (tables 6 and 7).

GROUND-WATER/SURFACE-WATER INTERACTION

Ground-water/surface-water interaction refers to the exchange of ground water with pond and stream waters across the sedimentary interface at the pond or stream bottom. Topics of particular relevance to the hydrology of the James Campbell National Wildlife Refuge are:

1. the degree to which stream and ditchflows in the greater coastal plain are maintained by ground-water discharge from the Koolau aquifer or by diffuse seepage from surficial sediments;
2. the degree to which Punamano Unit is fed laterally by springs and seeps at the inland margin of the marsh, compared with being fed by upward ground-water seepage through its pond bottoms; and
3. the degree to which Kii Unit ponds are fed by upward ground-water seepage or, conversely, the degree to which the ponds lose water by downward seepage or lateral seepage through the bordering ditch levees or berms.

Consideration of these issues requires a combination of regional- and local-scale interpretations. Therefore, a discussion of regional-scale hydrogeology is given before focusing in greater detail on the specific processes and geologic materials in the immediate subsurface beneath the ponds.

Regional-Scale Hydrogeology

Interpretations of the hydrogeology and depositional history in the vicinity of the Refuge area can aid in understanding the nature of ground-water flow from the regional ground-water flow system to the Refuge. Such interpretations can be made mainly from the geologic map of Oahu and its accompanying report (Stearns, 1939; Stearns and Vaksvik, 1935; a portion is reproduced in figure 16), and from a hydrogeologic cross section (fig. 17) derived from drilling logs and hydrologic data for wells in the area (unpub. data at the U.S. Geological Survey, Honolulu, Hawaii).

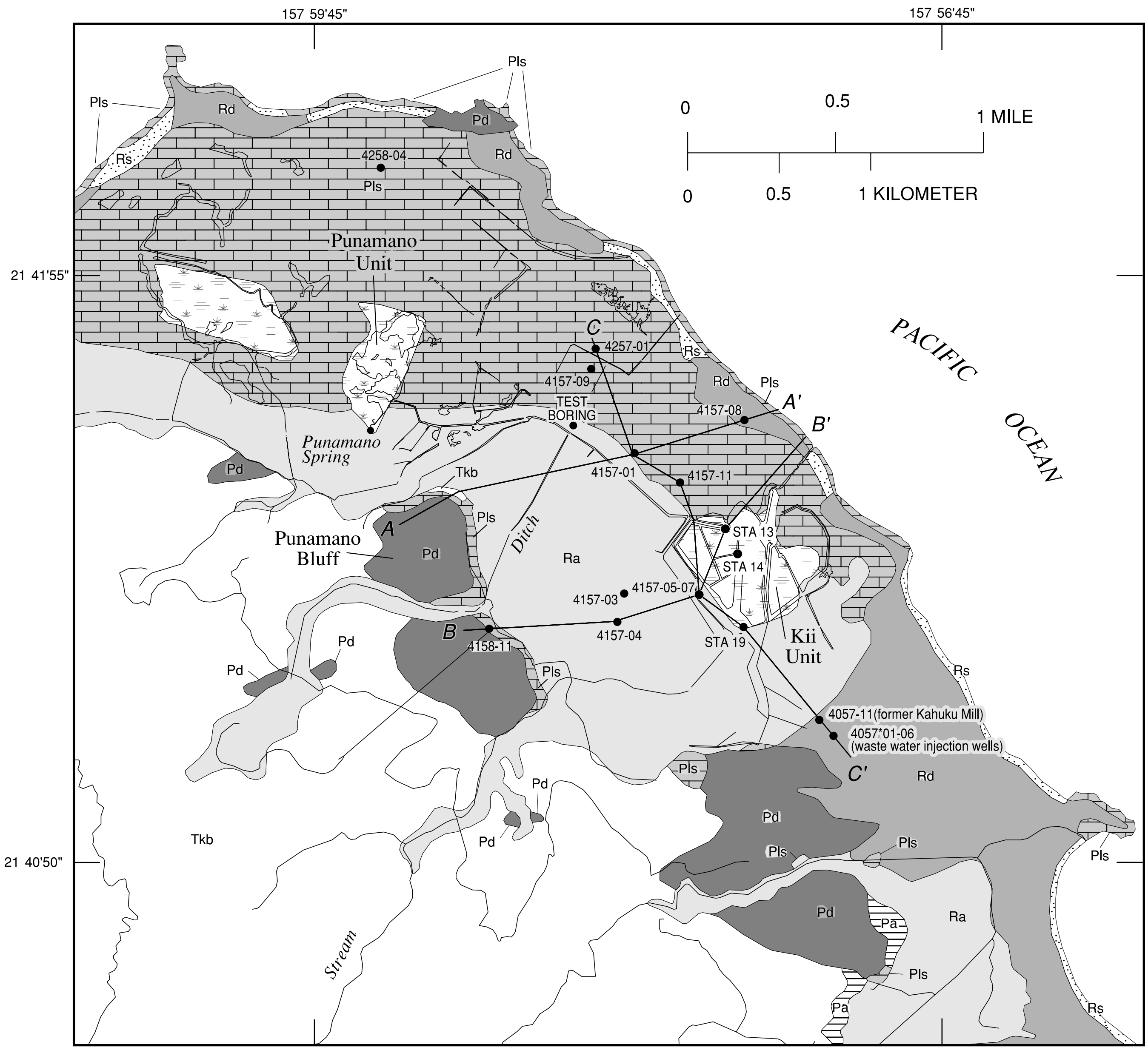
Principal Hydrogeologic Units

Just inland of the coastal plain in figure 16 are extensive uplands of Koolau Basalt (Tkb), which consists of lava flows, minor ash beds, and intrusive dikes of Pliocene to Pleistocene age (Doell and Dalrymple, 1973; Langenheim and Clague, 1987). Koolau Basalt extends thousands of feet below sea level and constitutes the highly permeable and regionally extensive Koolau aquifer (Hunt, 1996). Recharge in the Koolau uplands maintains a meteoric flow system within the aquifer, in the form of a freshwater lens that grades through a diffuse mixing zone into underlying saltwater (fig. 17). The coastal plain lies at the northern terminus of this flow system, and freshwater from the Koolau aquifer discharges upward into the overlying coastal-plain sediments. Intensive weathering of Koolau Basalt has left a mantle of readily erodible red soil and saprolite tens of feet thick over much of the uplands. One effect of the weathering is that alluvium washed from the uplands onto the coastal plain is mainly silty clay having low hydraulic conductivity.

Mapped sedimentary units in figure 16 include reef limestone (Pls), calcareous beach and dune sands (Rs, Rd), lithified calcareous dunes (Pd), and basaltic alluvium (Pa, Ra). The lithified dunes form low hills, most of which lie inland of Kamehameha Highway. One of these dunes (denoted as "Punamano Bluff") caps a sequence of raised Pleistocene reefs that overlie a subsurface ridge of Koolau Basalt (Stearns, 1970).

Although not specifically mapped in figure 16, one can postulate the presence of additional sedimentary lithofacies beneath the coastal plain from knowledge of modern depositional environments and drilling logs on Oahu. These include coralline rubble and calcareous sands that are associated with coral reefs; back-reef lagoonal sands, muds, and marls; and coarse beach rubble of mixed coral and basalt clasts that is deposited at the base of sea cliffs. Stearns (1970) identified such beach rubble in a detailed mapping of lithologic units at Punamano Bluff, and this information is incorporated in figure 17.

Reef limestone and associated calcareous deposits have high hydraulic conductivity (comparable to that of Koolau Basalt) and constitute patchy to extensive aquifers within the coastal-plain sequence. Alluvium, muds, and marls have low hydraulic conductivity and constitute confining units. Drilling logs for wells 4057-11 and 4057*01–06 were detailed enough to identify multiple limestone aquifers and intervening confining units (fig. 17). However at other wells, only limestone was penetrated within the depth of drilling (4257-01, 4157-09,



Base from U.S. Geological Survey digital line graph maps,
Kahuku quadrangle, 1:24,000

EXPLANATION

- MARSH (Holocene)
- Rs — BEACH SAND, CALCAREOUS (Holocene)
- Rd — SAND DUNES, CALCAREOUS (Holocene)
- Ra — ALLUVIUM (Holocene)
- Pa — ALLUVIUM (Pleistocene)
- Pls — LIMESTONE (Pleistocene)
- Pd — LITHIFIED DUNE, CALCAREOUS (Pleistocene)
- Tkb — KOOLAU BASALT (Pleistocene and Pliocene)
- *A*——*A′* LINE OF SECTION (figure 17)
- •4157-04 WELL AND STATE WELL NUMBER OR IDENTIFICATION

Figure 16. Geology of the Kahuku area (modified from Stearns, 1939), with locations of wells and lines of hydrogeologic cross sections near James Campbell National Wildlife Refuge, Oahu, Hawaii.

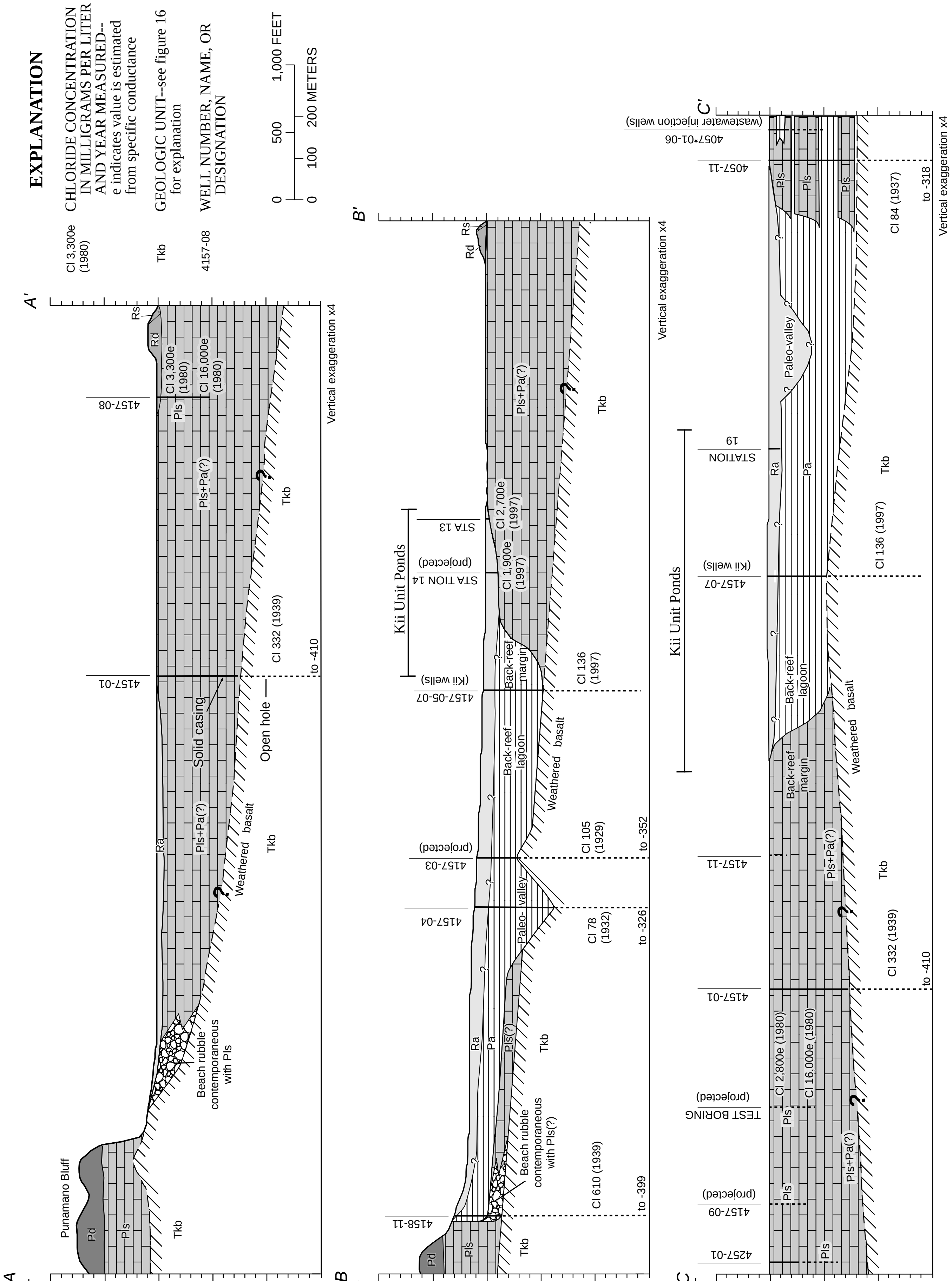


Figure 17. Hydrogeologic cross sections of the Kahuku area near James Campbell National Wildlife Refuge, Oahu, Hawaii.

Test Boring) or there was no lithologic log but the depth of solid casing was known (4157-01, 4157-03), which typically coincides with the top of the Koolau Basalt in this area. Thus, the actual stratigraphy within the coastal-plain sediments may be more complex than is portrayed in figure 17. Where limestone aquifers have been tapped by wells near the coast, they contain saline or brackish water. Sediments farther inland probably contain freshwater, particularly in higher parts of the alluvial fans, but no wells are situated properly to verify this.

The coastal-plain sediments confine the underlying Koolau aquifer, resulting in a confined potentiometric surface with heights of 10 to 15 ft above sea level in the vicinity of the Refuge, and unconfined water-table heights of 12 to 20 ft farther inland. If the coastal-plain sediments were absent, water levels in the Koolau aquifer would likely be only 2 to 3 ft above sea level, as is the case several miles to the southwest where the Koolau aquifer has been stripped of sediments by marine abrasion (Takasaki and Valenciano, 1969). Coastal-plain sediments are called "caprock" in Hawaii, in view of their confining effect on the volcanic-rock aquifers. Weathering of the uppermost several tens of feet of the Koolau aquifer may also contribute to its confinement. At the Kii artesian wells (4157-05–07) the land surface is about 6 ft above sea level and the potentiometric head in the wells is about 12 ft, which allows the wells to flow freely.

Sedimentary Depositional Sequence and Paleoenvironment

The depositional sequence of sedimentary deposits in the vicinity of the Refuge can be reconstructed from the preceding information and from established principles. Much of the Kahuku coastal plain is occupied by an emerged Pleistocene reef (the large expanse of limestone seaward of Punamano ditch in figure 16) that was deposited during the last interglacial highstand of sea level about 120,000 to 125,000 years ago (Stearns, 1970; 1978). The raised reefs at Punamano Bluff (and probably some of the deeper sediments in the coastal plain) were deposited earlier, in mid-Pleistocene time. From Stearns' (1970) detailed mapping, it is apparent that the sea cut a marine abrasion platform into raised reefs and Koolau Basalt at Punamano Bluff during the last interglacial high stand of the sea. Various interstream ridges of Koolau Basalt in the area would have been sea cliffs that were being undercut by waves at that time, and permeable coral reef and beach rubble would have been deposited directly on Koolau Basalt at the base of such cliffs, with the high-energy nearshore environment precluding deposition of any intervening low-permeability muds. Coral reefs would have extended offshore from the ridges, possibly merging offshore to form the large, seaward reef tract of limestone in figure 16.

At the same time, reef channels or embayments would have been aligned with the valleys, where the flow of fresh stream water and suspended sediment inhibited coral growth. In fact, Kii marsh probably marks a deep channel or back-reef lagoon that existed during the last interglacial and was later filled with alluvial mud (see fig. 17, sections B-B′ and C-C′, where 110 ft of alluvium, made up of brown, silty clay, overlie weathered Koolau Basalt to 104 ft below sea level at Kii wells 4157-05–07). Inland from Kii Unit, a paleo-valley is apparent at well 4157-04 (fig. 17, section B-B′), perhaps the ancestral drainage of Ohia Ai Gulch or Kalaeokahipa Gulch, both of which drain in this direction. A similar valley or reef channel may have existed in the vicinity of Punamano marsh, representing the ancestral drainage of Punahoolapa Gulch. This model of an extensive offshore reef tract with back-reef lagoon and reef channels is similar to the present configuration of Kaneohe Bay, farther south on the east coast of Oahu.

Sea level fell several hundred feet during the subsequent glacial stage lasting about 100,000 years, exposing the interglacial marine deposits. During this time, streams emerging from the uplands deposited their sediment load on the low-gradient coastal plain, forming prominent alluvial fans at the mouths of their valleys (the large area of alluvium in fig. 16), and perhaps filling in former reef channels and back-reef lagoons. The fans probably contain a large fraction of basaltic sand, gravel, and cobbles near the valley mouths, but the distal parts of the fans between Kamehameha Highway and Punamano ditch are composed mainly of compact, silty clay. The dune fields and beach sands near the present coast probably were deposited following the post-glacial Holocene rise of the sea to its present level about 6,000 years ago. The dune fields and alluvial fans obscure many of the key geologic contacts of the last interglacial marine transgression.

Nature of Ground-Water Discharge from the Koolau Aquifer

A key issue in this study is the extent to which ground-water discharge from the Koolau aquifer supplies water to the marshes of the Refuge. An explanation for the natural occurrence of Kii marsh is that it overlies a thick accumulation of channel-fill muds, and that ongoing compaction of the muds results in continued subsidence, maintaining this area as one of the lowest parts of the coastal plain. This is supported for at least the inland half of Kii Unit, given the 110-ft thickness of silty-clay alluvium at the Kii artesian wells. Ground-water seepage from the Koolau aquifer into the Kii ponds is likely to be small because of the low hydraulic conductivity of the intervening muds and clays.

An alternative hypothesis is required for Punamano marsh, much of which lies within limestone terrain. The ponds here may persist by dissolution of underlying calcareous material, fostered by organic decomposition and perhaps by upward seepage of freshwater from the underlying Koolau aquifer through reef limestone. The area around Punamano and Plum Tree Springs (fig. 2) appears to be a zone of concentrated discharge from the Koolau aquifer. This apparent zone of discharge, which likely is a principal source of water to the Punamano ponds, may be related to a buried ridge of Koolau Basalt that extends seaward from Punamano Bluff. Subsurface discharge from the Koolau aquifer probably enters beach rubble and limestone near Kamehameha Highway, subsequently flowing laterally toward the coast in the sediments. Some of the water emerges through a thin cover of alluvium near the inland edge of Punamano marsh (note that in fig. 16 Punamano Spring and the inland edge of the marsh are located about where the alluvium thins out to a feather edge).

Preferential ground-water discharge is to be expected just seaward of other bluffs or ridges of Koolau Basalt, most of which lie at the slope break between uplands and coastal plain. During the present study, base flow in Hospital ditch was traced upstream near a mapped outcrop of reef limestone at the base of the ridge of Koolau Basalt just west of the extensive lithified dune in figure 16. This bluff is similar to Punamano Bluff, apparently with similar preferential discharge from the Koolau aquifer. The flow here represents a direct contribution from the Koolau aquifer to the base flow of upper Hospital ditch.

Contributions to Ditch Base Flow from Surficial Sediments

In addition to ground-water discharge from the Koolau aquifer, discharge from surficial sediments provides another source of water to the lowland ditches. During this study, year-round streamflow was observed in Kii ditch at station 3 and in Hospital ditch at station 5. Flow was just a trickle during the dry season, however. Some of the flow at station 5 may have originated from the Koolau aquifer at the head of Hospital ditch. Regarding station 3, however, periods of no flow were observed at Kamehameha Highway bridge about 200 ft upstream, proving that Kii ditch gains base flow from alluvium in the reach between the highway and the gage. Streambeds at stations 3 and 5 are at altitudes of 2 to 3 ft above sea level and intercept the water table in the alluvium.

During repeated field visits to stations 3 and 5 throughout the year, a season-long recession of fair-weather low flow was visually apparent. This long recession probably represented sustained ground-water seepage from the thick alluvial fans, which had become saturated by heavy storms in November 1996 and January 1997. Inactive aquaculture ponds located on the alluvial fans were filled by the storms and required months of evaporation and infiltration to empty. In the aftermath of the wet season, bank seepage was visible part way up the steep bank of Kii ditch near station 3, several feet above the stream level. All lowland ditches that intersect the alluvial fans probably gain from ground-water seepage; however, this process was only observed along Kii ditch where there was no obscuring vegetation. Gains in ditchflow from the alluvial fans may form a substantial fraction of the 45 Mgal excess of stream outflow over stream inflow during 1997 (table 4).

In contrast, the streambed of Kalaeokahipa Gulch at station 2 was always dry during fair weather. The streambed altitude there is 9 ft above sea level, which apparently is not low enough to incise into the shallow water table in the alluvium.

Table 8. Logs of driven ground-water piezometers at the Kii Unit of James Campbell National Wildlife Refuge, Oahu, Hawaii
[Values are altitudes in feet above or below mean sea level, except for depth, which is in feet below pond or ditch bottom; --, not measured or not applicable; stations shown in figure 8]

Reference level and selected characteristics	Station 12 pond D	Station 13 Punamano ditch	Station 14 pond D	Station 15 pond C	Station 16 Hospital ditch	Station 17 pond A	Station 18 pond F
Top of casing	7.03	6.79	6.01	8.94	4.73	6.17	5.57
Pond or ditch water level just after driving	3.2	1.8	3.0	3.8	1.8	1.4	4.0
Pond or ditch bottom; soft muck	1.8	-0.2	2.6	3.3	0.6	0.7	3.4
Compact; refusal to manual pushing	-6.0	-2.4	-1.0	-3.7	-2.7	-2.3	2.0
Harder, more compact	-6.9	-3.2	-6.5	-7.1	-5.9	-4.2	-7.4
Ringing or refusal to driving	--	-4.2	--	--	--	-4.8	--
Stopped driving; bottom of wellpoint	-9.8	-4.2	-9.0	-7.1	-10.3	-4.8	-9.4
Midpoint of wellscreen (1 foot above tip of wellpoint)	-8.8	-3.2	-8.0	-6.1	-9.3	-3.8	-8.4
Hydraulic connection of wellscreen with surrounding materials	good	good	poor	poor	very poor	good	poor
Depth of well point, below pond or ditch bottom	11.6	4	11.6	10.4	10.9	5.5	12.8

Pond-Scale Hydrogeology of the Punamano and Kii Units

All of the ponds at the Punamano and Kii Units are underlain by several feet of black, organic-rich mud. The material beneath the organic mud at Punamano Unit is uncertain. At Kii Unit, the geologic log for the Kii artesian wells 4157-05–07 shows that the inland part of Kii Unit is underlain by 110 ft of alluvial clay. The geologic cross section (fig. 17) indicates that the thickness of alluvial deposits decreases seaward of the wells, and that reef limestone and associated calcareous sediments underlie the seaward parts of Kii Unit.

Hydrogeologic conditions in the shallow subsurface underlying the Kii Unit were studied by driving short-screened, steel piezometers to probe subsurface materials, and by recording water levels in these piezometers and in the overlying ponds and ditches. Locations of the piezometers are shown in figure 8, and table 8 contains the driving logs. The open, or screened, interval on the piezometers was 1 ft long, 0.5 to 1.5 ft from the driving tip.

Most of the piezometers felt as if they penetrated a layer of stiff, silty-clay alluvium beneath an upper layer of soft mud that ranged from 1.4 to 7.8 ft thick. At the more seaward piezometers (stations 12, 13, and 17) it was possible to develop good hydraulic connection between the wells and permeable material beneath the alluvium, which was probably calcareous sand or coralline rubble. Very hard material caused refusal to driving at stations 13 and 17 at depths of only 4 to 5.5 ft, and was probably coralline rubble or reef limestone. This is consistent with the nearby surface outcrop of reef limestone just to the north of these sites. The remaining piezometers had poorer hydraulic connection with subsurface materials: their screens had either gotten smeared with clay during driving or were simply open to clay at their final depths. These piezometers were driven to depths of 10.4 to 12.8 ft.

Four piezometers were outfitted with water-level recorders, and three of these (stations 12, 13, and 17) showed ground-water tides with maximum ranges of 2.2 to 2.4 ft (fig. 18). This equates to 73 to 80 percent of the ocean tidal range, as measured at the Kaneohe tide gage, indicating little attenuation of the tidal signal in the aquifer over distances of 1,100 to 2,200 ft inland from the ocean. In contrast, no tidal fluctuations were observed in the surface-water bodies at the piezometers. Surface-water hydrographs vary smoothly over several months except for station 13 which reflects the characteristic cycling pattern of the Kii outlet pump.

Daily means of the water-level data were calculated to filter out the tides and pumping cycles. Graphs of these data (fig. 19) clearly indicate the separate behavior of the surface- and ground-water bodies at stations 12, 13, and 17. Water-level trends are parallel at station 15, probably because the piezometer is screened in silty-clay alluvium and does not tap the carbonate aquifer that stations 12, 13, and 17 tap.

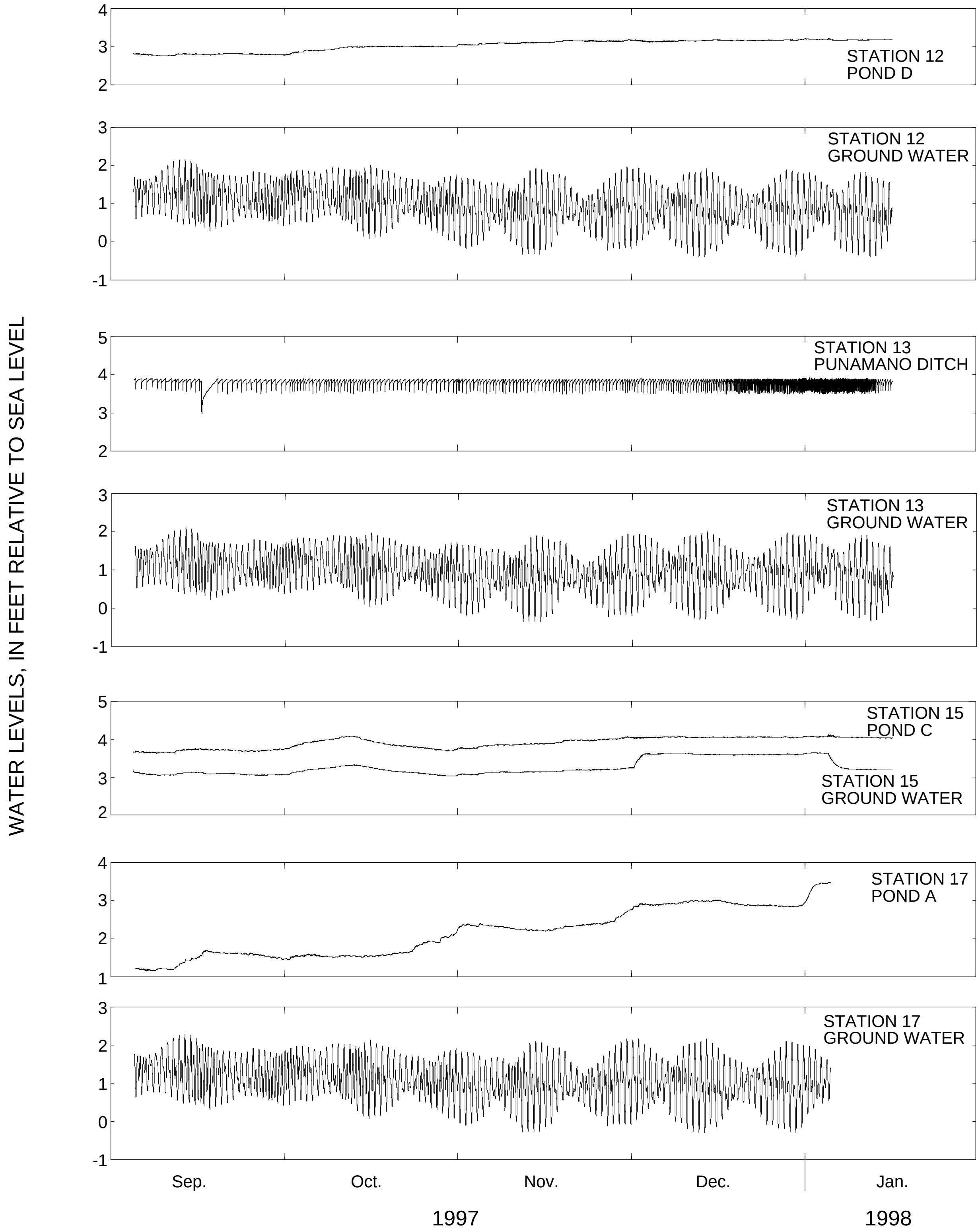


Figure 18. Ground-water levels in piezometers and surface-water levels in overlying ponds and ditches, September 1997 to January 1998, at Kii Unit, James Campbell National Wildlife Refuge, Oahu, Hawaii.

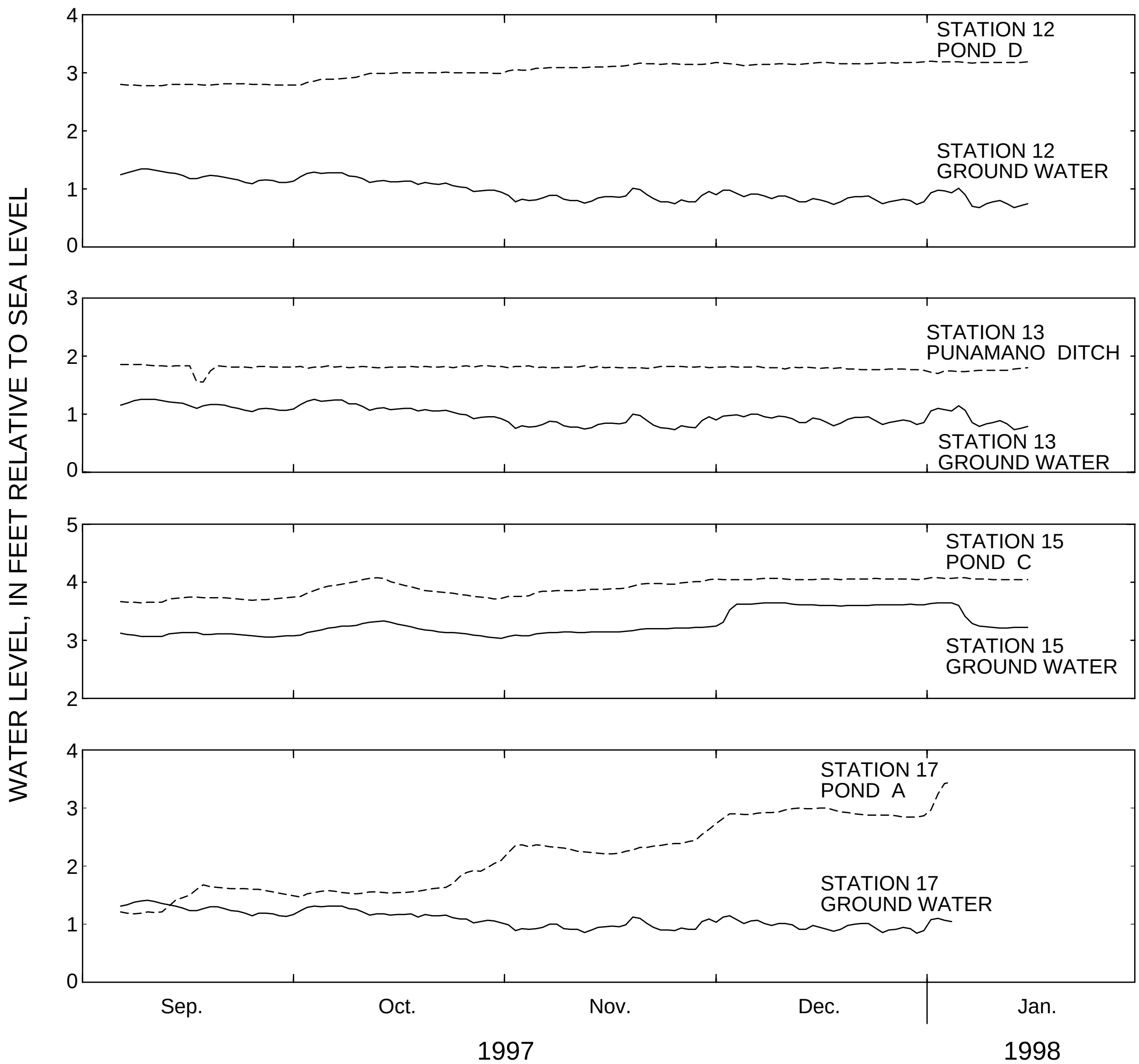


Figure 19. Daily mean ground-water and surface-water levels in piezometers and overlying ponds and ditches, September 1997 to January 1998, at Kii Unit, James Campbell National Wildlife Refuge, Oahu, Hawaii.

Synoptic water-level surveys were done at the network of piezometers, at nearby stream gages, and at USFWS pond staff gages on September 5, October 7, and December 10, 1997 (table 9). Daily mean levels were reported for stations equipped with water-level recorders in order to average out tidal and pumping cycles and short-term variability in pond levels. Several interpretations emerge from the more complete surveys in October and December:

1. the potentiometric level in the underlying carbonate aquifer was 1.3 ft above sea level in October and 1.0 ft in December; levels agreed to within 0.1 ft among stations 12, 13, and 17;
2. surface-water levels were higher than ground-water levels at all locations except stations 16 and 18;
3. pond levels ranged between about 3 to 4 ft, except for ponds A and E, which were less than 2 ft in October and less than 3 ft in December;
4. inner ditch levels (stations 7, 11, 13, and 16) were maintained at 1.8 ft or less by the Kii outlet pump and were lower than water levels in the adjacent ponds; and
5. outer ditch level at station 8 was 1.8 ft in October (lower than levels in adjacent ponds A and E) and 3.0 ft in December (higher than levels in adjacent ponds A and E).

Most of these relations are depicted schematically in figure 4.

Ground-Water and Surface-Water Salinity at Kii Unit Piezometers

Specific conductance was measured in ground-water and surface-water at each of the piezometer stations on November 14, 1997 to provide a proxy measure of salinity. Specific conductance in ground water ranged from 1,100 to 11,000 µS/cm and was greater in ground water than in overlying surface water at five of the seven piezometers (table 10). This range of conductance qualifies the ground water in the piezometers as slightly brackish to brackish, using the classification of Stewart and Kantrud (1971). The specific conductance of seawater at Kii ocean outlet was 52,000 µS/cm (see fig. 21), so the saltiest ground water was about one-fifth of seawater salinity.

Specific conductance in ground water generally was higher at more seaward sites and was high at the two sites where refusal to driving indicated that hard rock, probably limestone, was struck (7,100 µS/cm at station 13 and 11,000 µS/cm at station 17). The lowest conductance was recorded at the most inland site, station 18 (1,100 µS/cm), and likely reflects infiltration of pond water that has undergone slight evaporative concentration. Conductances of 5,000 µS/cm at pond D inland (station 14) and 9,500 µS/cm at Hospital ditch (station 16) suggest that the limestone aquifer containing brackish water extends inland under these sites. The limestone aquifer likely extends to some point between these sites and station 18 at pond F, and at least to the inland edge of pond D, 375 ft inland of Punamano ditch. The large difference in conductances between adjacent stations 15 and 16 (1,800 and 9,500 µS/cm) indicates that the piezometer at station 15 is just deep enough to tap a slight mixture of downward-infiltrating water from pond C (1,000 µS/cm) and the brackish water in the underlying carbonate aquifer tapped by piezometer 16 (9,500 µS/cm).

Specific conductance values in the ponds can be explained by slight evaporative concentration of well water (pond F is closest to the Kii artesian wells, ponds C and D are farther away and receive some or all of their water after it passes through pond F). The high conductance of 15,000 µS/cm in pond A (table 10), however, mainly reflects a management action by USFWS: the pond had been drained in August for maintenance and was allowed to refill with brackish outer-ditch water because well water was in short supply at the time. Specific conductance was lower in Hospital ditch than in Punamano ditch (1,000 and 2,400 µS/cm).

Ground-Water/Surface-Water Interaction at Kii Unit

Several inferences can be drawn regarding the relation of ground water to surface water at Kii Unit. Piezometers at stations 12, 13, 14, 16, and 17 tap an aquifer containing brackish water and having high hydraulic diffusivity, most likely consisting of reef limestone and associated coralline rubble and sand. Hydraulic diffusivity is the ratio of aquifer transmissivity to aquifer storage coefficient, and high diffusivity can arise from high transmissivity (or hydraulic conductivity), low storage coefficient (such as from confinement), or a combination of the two factors. Estimates of hydraulic conductivity in limestone aquifers on Oahu (from pumping tests and tidal analyses) commonly

Table 9. Ground-water and surface-water levels at selected stations on September 5, October 7, and December 10, 1997, James Campbell National Wildlife Refuge, Oahu, Hawaii

[Water levels in feet above mean sea level; values are daily mean levels from continuous recorders; at stations 12 through 18, both surface and ground water were measured; station shown on figures 6, 7, and 8]

Station	Surface-water body, ground-water body, or station name	September 5	October 7	December 10
	Ground-water piezometers with surface-water standpipes attached			
12	pond D	2.8	2.9	3.2
12	ground water	1.2	1.3	0.9
13	Punamano ditch	1.8	1.8	1.8
13	ground water	1.1	1.2	1.0
14	pond D inland	--	[2]2.8	[1]3.2
14	ground water	--	[2]3.0	[1]3.3
15	pond C	3.7	4.0	4.1
15	ground water	3.1	3.2	3.6
16	Hospital ditch	--	[2]1.3	[1]1.8
16	ground water	--	[2]2.9	[1]3.2
17	pond A	1.2	1.6	2.9
17	ground water	1.2	1.3	1.0
18	pond F	--	[2]3.9	[1]4.1
18	ground water	--	[2]4.0	[1]4.2
19	ground water[3]	--	1.8	--
	Surface-water stations			
1	Punamano ditch	2.4	2.5	2.5
3	Kii ditch	3.1	3.1	3.1
4	Kahuku storm drain	2.0	2.0	1.8
5	Hospital ditch	2.0	2.0	2.0
7	Kii outlet duckbill	1.8	1.8	1.8
8	Kii ocean outlet	2.0	2.3	3.0
11	Kii outlet pump	1.8	1.8	1.8
	Pond staff gages and recorders			
20	Pond A (staff)	--	[1]1.6	[1]2.9
21	Pond B (recorder)	3.6	3.6	3.6
22	Pond C (staff)	--	[1]4.0	[1]4.1
23	Pond C (staff) at kiosk	--	[1]4.0	[1]4.1
24	Pond D (staff)	--	[1]2.9	[1]3.2
25	Pond E (gate-in)	--	[1]1.9	[1]2.1
27	Pond F (staff)	--	[1]4.1	[1]4.1
28	Pond G (staff)	--	[1]3.2	[1]3.4
36	Punamano pond (recorder)	2.6	2.9	--

[1] Instantaneous manual measurement
[2] Manual measurement, September 17 (not measured on October 7)
[3] Station 19 is a monitoring well on land and has no corresponding surface-water measurement

Table 10. Specific conductance in ground-water piezometers and overlying surface-water bodies at Kii Unit, James Campbell National Wildlife Refuge, Hawaii, November 14, 1997

[Specific conductance in µS/cm (microsiemens per centimeter); stations shown in figure 8]

Station	Location	Ground water	Surface water
12	Pond D	2,900	3,600
13	Punamano ditch	7,100	2,400
14	Pond D inland	5,000	3,600
15	Pond C	1,800	1,000
16	Hospital ditch	9,500	1,000
17	Pond A	11,000	15,000
18	Pond F	1,100	700

exceed 10,000 ft/d (Dale, 1974; Williams and Liu, 1975; Khan, 1981; Oberdorfer and Peterson, 1985).

High hydraulic diffusivity is indicated by the presence of large-amplitude tidal fluctuations in piezometers 12, 13, and 17, and the lack of tidal damping over distances of 1,100 to 2,200 ft from the coast. Piezometers 14 and 16 probably tap this aquifer as well, judging from their high specific conductances (5,000 and 9,500 µS/cm), although recorders were not placed on these piezometers and so tidal fluctuations were not confirmed in them.

The limestone aquifer underlying Kii Unit is confined by the overlying silty-clay alluvium and pond-bottom muds. The hydraulic relation of ponds to aquifer can be described as semiperched, using the nomenclature of Meinzer (1923). That is, water in the ponds belongs to the same zone of saturation as in the aquifer (there is no intervening unsaturated zone) but water levels in the ponds are greater than the potentiometric level in the underlying aquifer because of the intervening layer of low-permeability mud and clay. The surface of the pond is the water table and is different than the potentiometric level in the aquifer.

The subbottom mud-and-clay confining unit apparently is very effective. A confining unit capable of fully damping out 2-ft tidal fluctuations over a vertical distance of only a few feet is sufficiently low in hydraulic conductivity that it will strongly inhibit ground-water/surface-water exchange. To a first approximation, then, it can be reasonably inferred that the ponds and ditches at Kii Unit are fairly well isolated from underlying ground water, and tend not to exchange water to any great degree. This contention is supported by the distinct differences in specific conductance between ground water and surface water at most of the piezometers (table 10).

The greatest potential for ground-water seepage is in the downward direction, because most pond levels and ditch levels are higher than ground-water potentiometric levels in the underlying aquifer. This is strictly true for the period of observation (September 5, 1996 through January 8, 1998), but probably is true of dry seasons in general at Kii Unit. It is not known if this pattern holds during the wet season or from year to year. However, the probable high hydraulic conductivity of the limestone aquifer would tend to preclude potentiometric levels from rising much higher than observed: water drains to the ocean too readily in such aquifers to build up much head.

The principal exception to the general pattern of downward gradients was at station 16 (table 9). At station 16, ground-water levels in October and December were 1.1 and 1.4 ft higher than the typical Hospital ditch level of 1.8 ft (the October ditch level of 1.3 ft apparently was measured during a drawdown cycle of the outlet pump). The piezometer at station 16 is 3.2 ft deeper than that at station 15, and ground-water levels at station 16 were consistently lower than at station 15 (0.3 ft lower in October, 0.4 ft in December). Therefore, ground-water levels at station 16 could reflect head loss along a curving ground-water flow path running downward from pond C at station 5 and curving laterally and then upward to discharge into Hospital ditch.

Regional Salinity Survey and Reconnaissance for Ground-Water Seepage

A reconnaissance survey was done throughout the coastal plain in the vicinity of the Refuge to measure specific conductance (a proxy measure of salinity) and temperature of surface water in ponds and ditches and to search for signs of ground-water seepage. The survey was done over 3 days, November 12–14, 1997, under dry-season conditions. The location of each measurement was determined in the field with a global positioning system (GPS) instrument.

Results of the survey are summarized in table 11 and figures 20 and 21. At locations where stratification was detected in the water column, two measurements were recorded: one at the top and one at the bottom of the water column; the bottom value was shown in

Table 11. Specific conductance and temperature of surface and ground waters on the Kahuku coastal plain in and near James Campbell National Wildlife Refuge, November 12–14, 1997

[Readings are given for both top and bottom of water column where stratification was detected; µS/cm, microsiemens per centimeter; °C, degrees Celsius; --, not measured or not applicable; in., inches]

Site (figs. 20 and 21)	Specific conductance (µS/cm)		Temperature (°C)		Remarks
	Top	Bottom	Top	Bottom	
1	2,400	--	24.0	--	Punamano ditch at west refuge fence; Nov. 12, 1030 hours
2	1,400	1,900	24.6	23.9	Punamano ditch just west of Campbell road crossing; water lilies
3	1,200	1,500	24.4	24.3	Punamano ditch
4	860	--	24.4	--	Punamano ditch
5	810	--	24.7	--	Punamano ditch, bend in ditch
6	790	--	24.9	--	Punamano ditch, end of open water; pickleweed seaward
7	780	--	24.6	--	Punamano ditch
8	760	--	24.3	--	Punamano ditch, 12-inch PVC pipeline crossing
9	750	--	24.7	--	Punamano ditch
10	740	--	24.7	--	Punamano ditch, limestone fragments in soil; ironwoods seaward
11	730	760	24.9	24.7	Punamano ditch, slough and pickleweed lie seaward; rain 1130 hour
12	720	--	24.2	--	Punamano ditch near shack, electricity lines run inland; grass in ditch
13	710	--	25.0	--	Punamano ditch
14	690	--	24.2	--	Punamano ditch at station 1, downstream of duckbill
15	700	--	24.0	--	Punamano ditch at station 1, upstream of culvert; rain stops 1150 hours
16	700	--	24.6	--	Punamano ditch at station 1, upstream of culvert; 1400 hours
17	680	730	24.5	24.6	Punamano ditch
18	670	--	23.9	--	Punamano ditch; cattails
19	4,600	9,100	27.1	--	Unnamed saline slough seaward of Punamano ditch; pickleweed; shallow, about 4 inches
20	19,000	--	26.1	--	Same slough; dead cattails, iron floc on bottom; possibly near margin of limestone aquifer or tidal influence
21	660	--	24.1	--	Punamano ditch; back to ditch after detour to slough
22	640	--	23.9	--	Last site on Punamano ditch; 1520 hours
23	3,000	3,300	24.2	--	Unnamed ditch, east side Nudist Camp road
24	2,200	--	24.3	--	Unnamed ditch, west side Nudist Camp road
25	900	--	23.6	--	Punamano north pond at U.S. Fish and Wildlife Service gage; Nov. 13
26	900	--	23.4	--	Punamano north pond; cattails
27	900	--	23.6	--	Punamano north pond; christmas berry
28	900	940	23.6	23.5	Punamano north pond; cattails; firm bottom with shells, coral (?)
29	890	--	23.7	--	Punamano north pond
30	900	--	23.7	--	Punamano north pond
31	880	--	23.5	--	Punamano north pond
32	880	--	23.7	--	Punamano north pond; christmas berry alcove; white clay bottom, sampled clay
33	900	--	23.8	--	Punamano north pond
34	900	--	23.8	--	Punamano north pond
35	890	--	25.0	--	Punamano south pond, small west part
36	880	--	25.8	--	Punamano south pond, small west part
37	740	--	24.8	--	Punamano south pond, crossed over into larger east part
38	720	--	24.7	--	Punamano south pond, large east part; line of poles, seaward end
39	720	--	24.8	--	Punamano south pond, large east part; another line of poles, west end
40	720	--	24.6	--	Punamano south pond, large east part
41	700	740	25.2	--	Punamano south pond, large east part
42	720	--	25.2	--	Punamano south pond, large east part
43	700	--	24.1	--	Punamano south pond, large east part
44	720	--	24.5	--	Punamano south pond, large east part
45	720	--	25.2	--	Punamano south pond, large east part
46	890	--	25.8	--	Punamano south pond, back to small west part; another line of poles, east end
47	880	--	23.0	--	Punamano Spring finger channel; 1335 hours
48	620	--	22.6	--	Plum Tree Spring
49	620	--	22.9	--	Unnamed ditch running inland from Plum Tree Spring
50	580	--	24.4	--	Same ditch, farther inland; many other ditches around
51	700	--	30.2	--	Pond F at piezometer 18; Nov. 14
52	1,100	--	25.7	--	Piezometer 18 ground water
53	740	--	29.2	--	Pond C, staff gage and gate near kiosk

Table 11. Specific conductance and temperature of surface and ground waters on the Kahuku coastal plain in and near James Campbell National Wildlife Refuge, November 12–14, 1997--Continued

[Readings are given for both top and bottom of water column where stratification was detected; µS/cm, microsiemens per centimeter; °C, degrees Celsius; --, not measured or not applicable; in., inches]

Site (figs. 20 and 21)	Specific conductance (µS/cm)		Temperature (°C)		Remarks
	Top	Bottom	Top	Bottom	
54	3,600	--	26.5	--	Pond D, inland end at piezometer 14
55	5,000	--	25.1	--	Piezometer 14 ground water
56	3,600	--	25.6	--	Pond D, seaward end at piezometer 12
57	2,900	--	25.6	--	Piezometer 12 ground water
58	2,400	--	26.5	--	Punamano ditch at piezometer 13
59	7,100	--	26.2	--	Piezometer 13 ground water
60	1,800	--	26.5	--	Pond G, seaward end at gate to Punamano ditch
61	1,300	--	26.3	--	Pond G, inland end at flowing pipe from artesian wells
62	660	--	23.3	--	Pond F inland, in flowstream from pipe flow (well water)
63	680	--	27.1	--	Pond F inland, 20 ft east of last site
64	730	--	28.4	--	Pond F seaward, across berm from site 62
65	650	--	21.9	--	Kii artesian wells sump
66	1,000	--	27.3	--	Pond C, seaward end
67	2,900	--	26.6	--	Blind ditch near windmill
68	1,000	--	27.5	--	Pond C at piezometer 15
69	1,800	--	25.9	--	Piezometer 15 ground water
70	1,000	--	26.1	--	Hospital ditch at piezometer 16
71	9,500	--	25.0	--	Piezometer 16 ground water
72	890	--	28.8	--	Pond B at staff gage and gate to pond A
73	15,000	--	28.1	--	Pond A at piezometer 17
74	11,000	--	28.0	--	Piezometer 17 ground water
75	5,600	--	26.5	--	Outer ditch, just west across berm from pond A at piezometer 17
76	27,000	--	28.5	--	Raboy ditch, just north across berm from pond A at piezometer 17
77	5,000	--	26.9	--	Ocean outlet ditch at station 8
78	9,000	--	29.6	--	Ocean outlet ditch just upstream of partly damming sand plug
79	52,000	--	25.8	--	Ocean at ditch outlet; sample seawater at edge of limestone shelf
80	2,500	--	27.8	--	Station 7, upstream of culvert, Punamano ditch
81	4,700	9,900	26.7	25.4	Station 7, downstream of duckbill, outer ditch
82	4,700	21,000	27.2	26.6	Outer ditch east of pond E seaward gate
83	4,900	--	27.9	--	Pond E seaward, at gate to outer ditch
84	2,300	--	27.3	--	Pond E inland, at gate to Punamano ditch
85	5,500	16,000	26.8	26.2	Outer ditch at outer flood-relief swale, station 34
86	1,300	--	26.3	--	Punamano ditch at outer flood-relief swale, station 34
87	980	--	27.1	--	Hospital ditch at inner flood-relief swale, station 33
88	1,000	--	26.3	--	Punamano ditch at inner flood-relief swale, station 33
89	2,900	--	26.2	--	Blind ditch at inner flood-relief swale, station 33
90	2,900	--	26.8	--	Blind ditch, halfway to windmill
91	1,500	--	26.8	--	Punamano ditch, halfway to windmill
92	2,100	--	27.5	--	Punamano ditch at windmill
93	2,300	--	27.2	--	Punamano ditch halfway from piezometer 13 to west refuge fence
94	2,400	--	27.2	--	Punamano ditch at west refuge fence
95	1,100	--	27.2	--	Hospital ditch at pond C staff gage
96	770	1,300	26.6	26.3	Hospital ditch halfway to refuge fence
97	590	--	25.2	--	Hospital ditch at refuge fence
98	860	--	28.9	--	Pond C, inland corner by sewage treatment plant
99	3,500	4,300	26.2	25.3	Kii ditch, seaward end by sewage treatment plant
100	2,200	--	24.5	--	Kii ditch, halfway to station 3
101	1,400	--	23.2	--	Kii ditch at station 3, downstream side of checkdam
102	1,400	--	24.2	--	Kii ditch at station 3, upstream side of checkdam
103	1,200	--	23.5	--	Kii ditch at Kamehameha Highway bridge
104	470	--	25.1	--	Hospital ditch at station 5
105	440	--	27.2	--	Hospital ditch inland of Kamehameha Highway
106	460	--	24.7	--	Hospital ditch further inland
107	430	--	21.8	--	Hospital ditch near source; shallow, flowing stream over sand channel

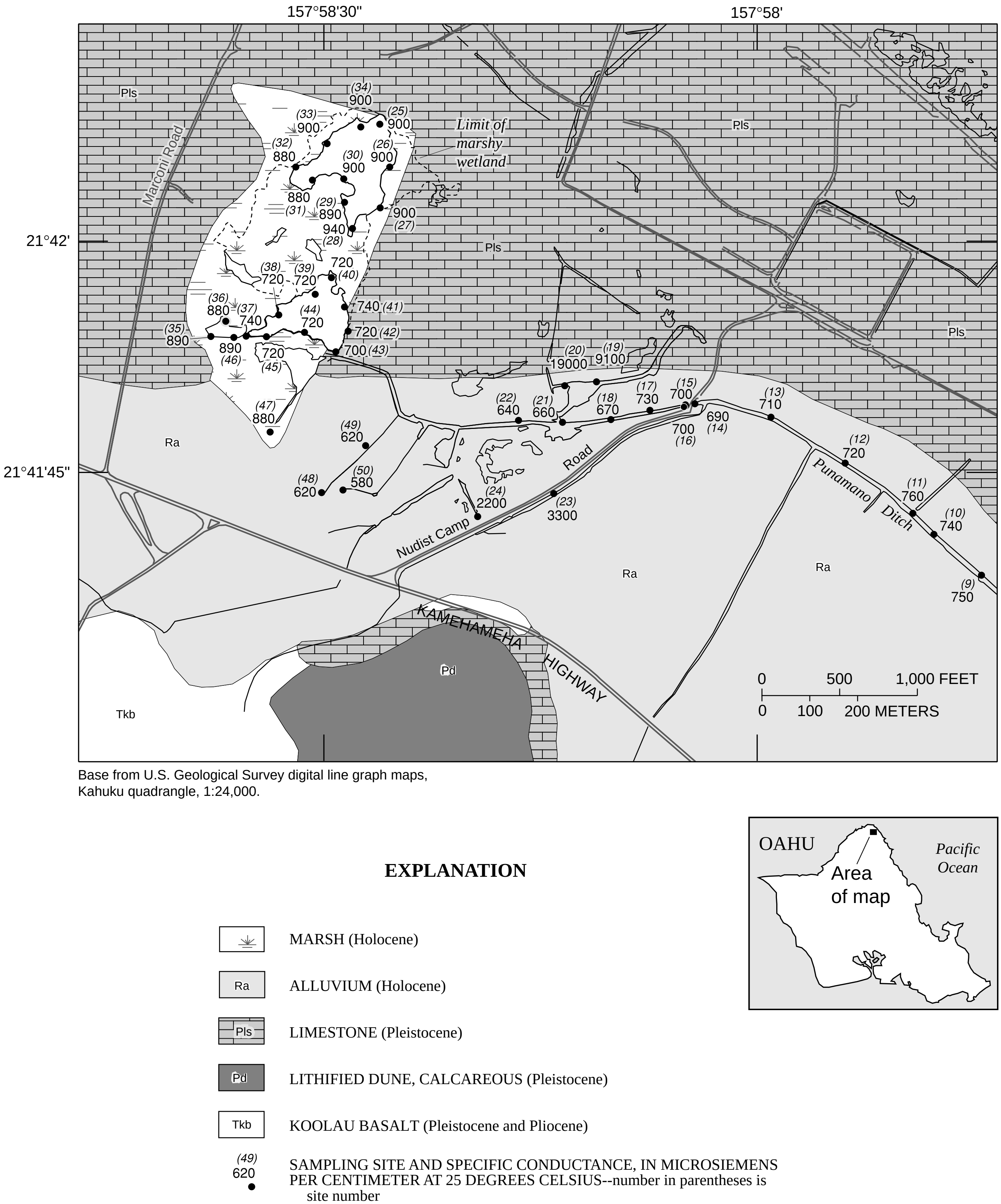
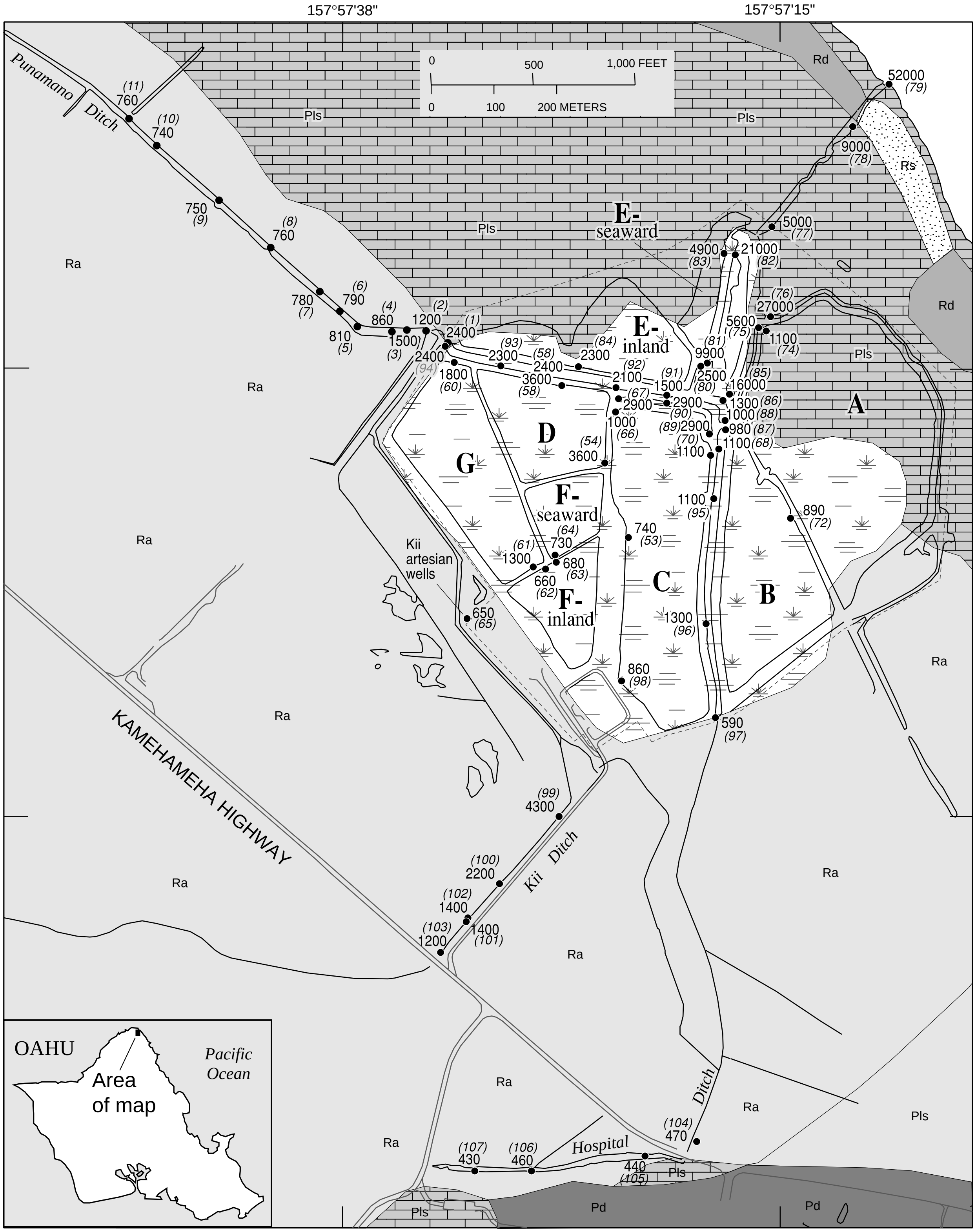


Figure 20. Specific conductance of surface-water bodies in and near Punamano Unit, James Campbell National Wildlife Refuge, Oahu, Hawaii, November 12-14, 1997.



Base from U.S. Geological Survey digital line graph maps,
Kahuku quadrangle, 1:24,000

EXPLANATION

(marsh symbol)	MARSH (Holocene)	Ra	ALLUVIUM (Holocene)
Rs	BEACH SAND, CALCAREOUS (Holocene)	Pls	LIMESTONE (Pleistocene)
Rd	SAND DUNES, CALCAREOUS (Holocene)	Pd	LITHIFIED DUNE, CALCAREOUS (Pleistocene)

(103) 1200 ● SAMPLING SITE AND SPECIFIC CONDUCTANCE, IN MICROSIEMENS PER CENTIMETER AT 25 DEGREES CELSIUS-- number in parentheses is site number

Figure 21. Specific conductance of surface-water bodies in and near Kii Unit, James Campbell National Wildlife Refuge, Oahu, Hawaii, November 12-14, 1997.

figures 20 and 21. For reference, the specific conductance in seawater at Kii ocean outlet (site 79) was 52,000 µS/cm. Takasaki and Valenciano (1969) showed correlations between specific conductance and chloride concentration. For water having contacted calcareous material, a conductance of 600 µS/cm corresponded to a chloride concentration of 100 mg/L, and 3,000 µS/cm corresponded to 1,000 mg/L. Chloride concentration in seawater is about 19,500 mg/L.

Salinity at Punamano Unit

At Punamano Unit (fig. 20), the freshest water measured was at site 50 (580 µS/cm and 24.4°C), near the head of a ditch just to the east of Plum Tree Spring. The coldest water was at Plum Tree Spring at site 48 (22.6°C and 620 µS/cm). Punamano Spring at site 47 measured 880 µS/cm and 23.0°C. The low conductance and temperature at these sites identifies them as probable Koolau aquifer discharge that has not been much affected by heating or evaporative concentration. For comparison, water from the Kii artesian wells (site 65 in fig. 21), which is known to come from the Koolau aquifer, had a conductance of 650 µS/cm and a temperature of 21.9°C. Flow at both Punamano and Plum Tree Springs is not pronounced; flow is discernible if bottom sediment is disturbed, but it is not readily apparent otherwise.

Conductance is low in Punamano ditch between Plum Tree Spring and gaging station 1 at Nudist Camp Road, and between the spring and Punamano south pond (sites 35 to 46), where conductance is 700 to 740 µS/cm. The Plum Tree Spring area is probably a main source of water, both to Punamano south pond and to eastward flowing water in Punamano ditch. That is, flow from the Plum Tree Spring area may be great enough that it diverges both left and right where the ditches leading from the spring intersect Punamano ditch.

Other ponds at Punamano have conductances of 880 to 940 µS/cm. This could represent evaporative concentration of fresher water from Plum Tree Spring, separate sources of water in the ponds themselves, or mixtures of several water sources. Water in Punamano north pond (sites 25 to 34) is colder at 23.7°C than the ponds to the south of it. This could possibly signify a separate, local source of colder, Koolau-derived discharge; or, it may simply result from evaporative cooling (north pond is the largest pond and is subject to the longest wind fetch).

Several side ditches in the Punamano area have much higher conductance than the springs and ponds. Along Nudist Camp Road, conductances of 3,300 and 2,200 µS/cm were measured in ditches just east and west of the road, respectively (sites 23 and 24). These values may reflect evaporative concentration of fresher water under stagnant conditions, or residual salinity from the defunct saltwater aquaculture ponds east of the road.

Seaward of Punamano ditch, near the wishbone-shaped ditch, conductances of 9,100 and 19,000 µS/cm were measured at sites 19 and 20, indicating brackish to subsaline waters. The area near sites 19 and 20 is a shallow slough with salt-tolerant vegetation and a bottom of calcareous sand. The pattern of patchy vegetation and bare sand gave a visual impression of a tidal flat with varying water level. Dead cattails were noted, as was an iron floc on the bottom of the slough. Such high values of conductance this far inland are unusual and may be due to brackish water from the limestone aquifer that lies just seaward of these sites.

East of Nudist Camp road, sites 9 through 14 along Punamano ditch have conductances of 700 to 760 µS/cm, not much different from the fresher waters near the springs, and perhaps representing slight evaporative concentration or diffuse ground-water gains along the ditch. No abrupt contrasts in conductance or temperature were apparent that might indicate a strong point-source of seepage in this reach.

Salinity at Kii Unit

The freshest water measured in the Kii area (fig. 21) was at site 107 near the headwaters of Hospital ditch (430 µS/cm and 21.8°C). The flow in Hospital ditch was not traced all the way to its source, but Koolau Basalt and limestone and lithified dunes of Pleistocene age are mapped immediately south of site 107 on Hospital ditch (fig. 17). Flow in Hospital ditch probably is ground water discharging from the Koolau aquifer, which is considerably fresher and slightly colder at this inland location than water from the Kii artesian wells (650 µS/cm, 21.9°C).

In nearby Kii ditch, conductance increases from 1,200 µS/cm at Kamehameha Highway (site 103) to 4,300 µS/cm at site 99 just 1,000 ft downstream. This increase in conductance clearly indicates a gain in stream discharge along this reach, and that the new source of water has higher specific conductance than upstream water. The exact nature of the source is not clear.

Along Punamano ditch, conductance increases from 720 to 860 µS/cm from site 11 to the southeast, until saltier water is encountered at the confluence with Kii ditch. The conductance of 2,400 µS/cm at the confluence (sites 1 and 94) indicates roughly equal contributions from Punamano and Kii ditches, assuming mixing of waters having conductances of 760 µS/cm (site 8) and 4,300 µS/cm (site 99). Within Kii Unit, conductance decreases from 2,400 to 1,000 µS/cm along Punamano ditch from the west fence (site 94) to the swale at Hospital ditch (site 88). This decrease probably reflects progressive blending with Hospital ditch water, which ranges from 590 to 1,300 µS/cm inside the refuge fence (sites 87, 95 to 97), and perhaps to seepage or releases from ponds C or B.

Water in blind ditch (sites 67, 89 to 90) is 2,900 µS/cm, which is higher than in adjacent ditches and may be a good example of evaporative concentration. This ditch is stagnant, with no throughflow, and rainfall and seepage to the ditch are less likely to keep pace with evaporation than in adjacent ditches, which also receive surface-water inputs.

Water in the outer ditch is stratified like an estuary at site 82, with brackish water of 4,700 µS/cm at the top of the water column and subsaline water of 21,000 µS/cm at the bottom. Water in Raboy ditch (site 76) was 27,000 µS/cm, the highest on-land conductance measured. Water in the outer ditch may reflect seawater overwash, with fresher water from the inner ditches floating on top of deeper, subsaline water. The subsaline water in the lower part of the water column in the outer ditch may reflect ground-water gains as well, or dilution and incomplete mixing of seawater with discharge from the Kii Ponds. Raboy ditch is shallow, however, and not stratified. Hence, Raboy ditch might gain brackish or subsaline ground water by upward seepage from the shallow limestone aquifer in that vicinity, with evaporative concentration perhaps further increasing the salinity (Raboy ditch is nearly stagnant, and evaporative concentration would be progressive during dry periods).

Conductance varies substantially among the ponds, reflecting different water sources and the order of water routing from pond to pond. The Kii artesian wells produced water at 650 µS/cm and 21.9°C on the day of the survey (site 65). This water is fed to the ponds, some in succession. Ponds B, C, F, and G are fed directly by piped water from the wells, whereas pond D is fed from pond F, and pond A is fed from pond B. Ponds E-inland and E-seaward have water-control structures that supply them with water from Punamano ditch and outer ditch, respectively. Pond A also has a water-control structure to the outer ditch, from which it was refilled during the fall of 1997 after having been drained for maintenance in August.

Table 12 summarizes specific conductance readings for the Kii ponds, grouped in rough order of water routing or water source. Some of the ponds were sampled at more than one location.

Conductances in ponds B, C, and F appear to reflect slight evaporative concentration of the well water. Ponds G and D have conductances that are 2 to 5.5 times higher than that of well water. These ponds presumably have lower flushing rates and longer residence times, allowing additional evaporative concentration. This is particularly reasonable for pond D, which receives its water from pond F. The higher conductances in ponds G and D probably did not arise from backflow of brackish Punamano ditch water through the water-control structures, or from upward seepage of brackish ground water, because the typical pond levels of 3 to 4 ft were higher than ditch levels since late January (fig. 11, station 7) and higher than ground-water levels since early September (fig. 19) or before.

Pond E-inland is fed from Punamano ditch, whereas pond E-seaward is fed from outer ditch, which would explain the higher conductance in the seaward pond. Pond A was refilled from the outer ditch progressively through the fall of 1997 after being drained in August 1997 for maintenance (M. Silbernagle, USFWS Haleiwa Office, written commun., 1999), which explains the high conductance there (the highest of all the ponds).

Pond A had the thinnest layer of low-permeability material on the pond bottom and none of the stiff, silty-clay alluvium that was present at other piezometers (table 8). This thin mud cover could be areally patchy, allowing upward seepage of brackish ground water from the underlying limestone aquifer. However, upward seepage can only occur if there is an upward gradient (ground-water level greater than surface-water level). On the basis of daily mean levels (fig. 19), such a condition was observed only during the first week of

Table 12. Sources of water to ponds at Kii Unit, and specific conductance in the ponds and in the Kii artesian wells, November 14, 1997, James Campbell National Wildlife Refuge, Hawaii

Pond and source of water	Specific conductance (μS/cm)	Site (fig. 21)
Kii artesian wells	650	65
Fed directly from Kii wells:		
Pond B	890	72
Pond C-inland	860	98
Pond C-seaward	1,000	66
Pond F-inland	680	63
Pond F-seaward	730	64
Pond G (inland)	1,300	61
Pond G (seaward)	1,800	60
Fed from pond F:		
Pond D-inland	3,600	54
Pond D-seaward	3,600	56
Fed from Punamano and outer ditches:		
Pond E-inland	2,300	84
Pond E-seaward	4,900	83
Fed from pond B and outer ditch:		
Pond A	15,000	73

observations in September 1997 at station 17, at a time when pond A remained mostly drained.

Previous Salinity Observations

Takasaki and Valenciano (1969, their fig. 21) conducted a reconnaissance salinity survey in 1963, reporting chloride concentration rather than specific conductance. Their survey was done when sugarcane was being grown on the coastal plain and being irrigated with water from inland wells, many of which produced brackish water as a result of heavy pumping. The chloride concentrations they reported at sites in the ditches and marshes equate to specific conductances about 2 to 7 times higher than observed in this study. However, much has changed in terms of land use, irrigation practices, and ditch management (duckbill valves compared with flap valves), and the earlier results may have little relevance to present conditions.

More recently, USFWS has recorded high salinities in the ditches at times when saltwater aquaculture was prevalent (unpub. data, U.S. Fish and Wildlife Service, Haleiwa, Hawaii). Salinities as high as 14 and 22 parts per thousand (ppt) were recorded just upstream and downstream of the tidal valve at Punamano ditch station 1 on January 1, 1994 (the flap valve in place at the time was known to leak). Similarly, salinity in pond E has been as high as 22 to 26 ppt when saltwater aquaculture effluent was being discharged to the ditches (M. Silbernagle, U.S. Fish and Wildlife Service, Haleiwa, Hawaii, oral commun., 1995). For comparison, the salinity of seawater at Kii outlet ditch is estimated at 34.2 ppt on the basis of the specific conductance measured there in our survey. The relevance of these earlier salinity measurements by USFWS is that they may typify conditions that would accompany saltwater aquaculture if similar disposal methods were to be practiced (disposing saltwater effluents directly to Punamano ditch).

Potential Migration of Wastewater from the Kahuku Injection Wells

In the planning stages of this study, there was concern over the possibility that wastewater effluent from Kahuku sewage treatment plant might migrate to Kii Unit and affect the surface environment of the Refuge there. It was known that wastewater from the plant is disposed of using injection wells, which initially were thought to be onsite at the treatment plant at Kii Unit. However, the six wastewater injection wells are actually 0.45 mi away, at the old Kahuku Mill. Wells 4057*01-06 inject the wastewater into confined limestone aquifers and alluvium as shown in figure 17. Given the distance of the wells from Kii Unit, the confinement of the receiving aquifers at the injection wells, and the apparent discontinuity of those aquifers between Kahuku Mill and Kii Unit, it is unlikely that wastewater effluent can migrate to Kii Unit through subsurface sedimentary aquifers. It is even less likely that wastewater effluent can migrate to the Kii artesian wells, given the buoyancy of domestic wastewater in a saltwater environment within the limestone aquifers, and the fact that the Kii wells tap the underlying Koolau aquifer, which is confined and has an artesian head of about 12 ft that drives prevailing upward flow into the overlying sediments.

WATER BUDGETS FOR THE PUNAMANO AND KII UNITS

Water budgets were computed for ponds and wetlands at Punamano Unit and for ponds at Kii Unit to examine the balance between water sources and consumptive uses. The budgets were computed monthly for calendar year 1997 and summed to provide budget results for the entire year. A diagram showing the terms used in the water budgets for the Refuge is shown in figure 22.

At Punamano Unit the budget was computed for the entire marsh complex, including the open-water ponds and surrounding vegetated wetlands covering 27.5 acres (fig. 2 and table 13). At Kii Unit the water budget of the ponds that receive inflow from the Kii artesian wells is of most interest, and so pond E and the intervening ditches, berms, and incidental patches of wetlands were omitted from the budget, leaving a budget area of 65.7 acres (fig. 3 and table 13).

Water-Budget Equations

A water budget should ideally account for the principal hydrologic inflows and outflows in the area of interest. In such a situation, net inflow should equal net outflow, plus the changes in storage in the area:

$$\text{Inflow} = \text{Outflow} + \Delta\text{Storage} \qquad (2)$$

By expanding with terms appropriate to the Refuge this becomes:

$$\text{Rain} + SW_{in} + GW_{in} + \text{Wells} = ET + SW_{out} + GW_{out} + \Delta\text{Storage} \qquad (3)$$

where:

- Rain = direct rainfall (precipitation) over the budget area;
- SW_{in} = surface-water inflow to the area;
- GW_{in} = ground-water inflow to the area;
- Wells = ground-water supplied by the Kii artesian wells (Kii Unit only);
- ET = evapotranspiration from the area (the combination of direct evaporation and transpiration by plants);
- SW_{out} = surface-water outflow from the area;
- GW_{out} = ground-water outflow from the area;
- ΔStorage = change in the amount of water stored within the area.

Practically, however, some hydrologic components are impossible to measure or can be considered insignificant, and are omitted to derive simplified budget equations. In this case, inflow is unlikely to equal outflow plus change in storage. The net water budget that results includes a residual term that in theory is equal to the net total of all the unmeasured terms, plus any errors or inaccuracies in the budget:

$$\text{Inflow} = \text{Outflow} + \Delta\text{Storage} + \text{Residual} \qquad (4)$$

Equation 4 can be rearranged to give a slightly different perspective:

$$\text{Inflow} - \text{Outflow} - \Delta\text{Storage} = \text{Residual} \qquad (5)$$

Punamano marsh receives direct rainfall and surface-water runoff from the uplands and surrounding land, evaporates and transpires water, discharges surface water through Punamano ditch (measured at station 1), and may gain or lose ground water. The ground-water terms cannot be estimated independently and so are included in the residual, resulting in this simplified water-budget equation for Punamano Unit:

$$\text{Rain} + SW_{in} = ET + SW_{out} + \Delta\text{Storage} + \text{Residual} \qquad (6)$$

where the Residual contains GW_{in} and GW_{out}, as well as any budget inaccuracies.

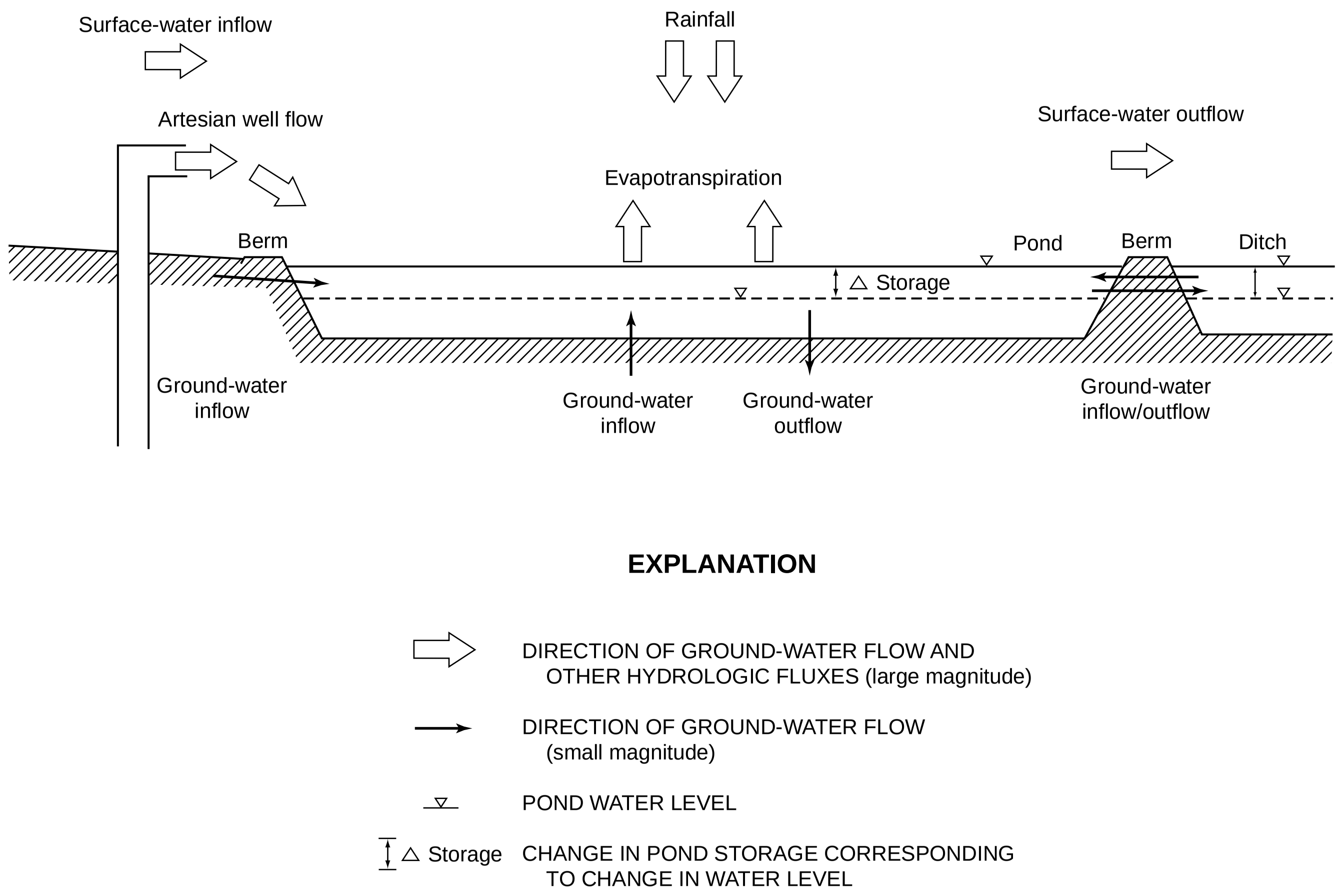


Figure 22. Terms in the water budgets for Punamano and Kii Units, James Campbell National Wildlife Refuge, Oahu, Hawaii.

Table 13. Surface areas of ponds and wetlands, James Campbell National Wildlife Refuge, Hawaii

[Areas were determined by geographic information system (GIS), using pond and wetland outlines defined on aerial photographs and registered to digital topographic maps provided by the U.S. Army Corps of Engineers; ponds shown on figures 2 and 3]

Pond or wetland	Surface area (acre)
Punamano Unit	
North pond	5.6
West pond large	0.4
West pond medium	0.2
West pond small	0.1
South pond large	3.6
South pond small	0.5
Spring pond	1.4
Wetland, not including ponds	15.7
Punamano ponds total	11.8
Ponds and wetlands total	27.5
Kii Unit	
Pond A	21.1
Pond B	9.3
Pond C	14.3
Pond D	5.8
Pond E-seaward	1.9
Pond E-inland	6.3
Pond F-seaward	2.6
Pond F-inland	3.7
Pond G	8.9
Kii ponds total	73.9
Kii ponds minus ponds E	65.7
Kii fenced area	116.0

The Kii Unit ponds (minus pond E) receive direct rainfall and inflow from the Kii artesian wells, evaporate and transpire water, and may gain or lose ground water. To a first approximation, the Kii ponds are an isolated hydrologic system, and surface-water inflow and outflow are thought to be negligible for the ponds. Water-control structures connect several of the Kii ponds to adjacent ditches, but flashboards in the controls are usually positioned high enough so that little or no ditch water enters the ponds. Small amounts of water may flow out of the ponds over the flashboards, but USFWS Refuge managers attempt to minimize this loss. Therefore, the ground-water terms and any unmeasured surface-water flows are included in the residual to give the following simplified water-budget equation for Kii Unit:

$$\text{Rain} + \text{Wells} = \text{ET} + \Delta\text{Storage} + \text{Residual} \qquad (7)$$

where the Residual contains GW_{in}, GW_{out}, SW_{in}, SW_{out}, and any budget inaccuracies.

Required Data

Monthly measurements of rainfall and potential evaporation (PE) are listed in table 14. A "composite full-month rainfall" total for each month was derived by using data from meteorology station 10 as a base, and supplementing with data from USFWS meteorology station 35 where data were missing at station 10. Potential evaporation was computed using the Penman method (Penman, 1948) and various meteorologic variables recorded during the study (T.W. Giambelluca and M.A. Nullet, University of Hawaii, written commun., 1998). "Full-month PE" denotes values that were adjusted by simple pro-rating to account for missing days of data. Missing values of PE for November and December 1996 were estimated as the average of values in prior and subsequent years for the respective months. The monthly values of rainfall and potential evaporation measured at Kii Unit were applied at both the Punamano and Kii Units, assuming that evapotranspiration (ET) is equal to the full monthly amount of potential evaporation (PE). This assumption is reasonable for the ponds and wetlands of the Refuge, where evapotranspiration is unlikely to be limited by available water (that is, the open-water ponds and scattered areas of marsh plants present unlimited "evaporation opportunity").

At Punamano Unit, station 1 discharge values in table 4 constituted the surface-water outflows, and surface-water inflows from the inland watershed that is tributary to Punamano Unit (area 1b in table 1 and fig. 5) were estimated from station 1 discharge values by area-weighted pro-rating.

At Kii Unit, a main component of the budget is inflow from the Kii artesian wells. Monthly values of ground-water flow from the wells, recorded by totalizing flow meters, were obtained from USFWS (M. Silbernagle, USFWS Haleiwa Office, written commun., 1998). Some pro-rating was applied across month boundaries to adjust values for which meter readings had been taken in mid-month.

Table 14. Monthly rainfall in the Kahuku uplands, and rainfall and potential evaporation at the Kii Unit of James Campbell National Wildlife Refuge, Oahu, Hawaii, 1995–97

[Values in inches; PE, potential evaporation; --, not available or not applicable; computed by the Penman method; USFWS, U.S. Fish and Wildlfe]

Month	Upland	Kii Unit						
	Station 9 rain gage	Station 35 USFWS rain gage[1]	Station 10 rain gage[2]	Station 10 number of days with rain record[3]	Station 10 PE	Station 10 number of days with PE record[3]	Composite full-month rainfall[4]	Full-month PE[5]
1995								
January	--	0.92	--	--	--	--	0.92	--
February	--	3.63	--	--	--	--	3.63	--
March	--	3.69	--	--	--	--	3.69	--
April	--	4.09	--	--	--	--	4.09	--
May	--	0.81	0.31	22	5.73	22	0.81	8.07
June	--	1.14	1.14	--	7.29	--	1.14	7.29
July	--	1.63	1.56	--	7.71	--	1.56	7.71
August	--	2.05	1.74	--	7.37	29	1.74	7.88
September	--	2.22	1.89	--	2.04	10	1.89	6.12
October	--	2.14	3.17	--	3.42	18	3.17	5.89
November	--	1.40	6.28	--	3.85	--	6.28	3.85
December	--	0.47	4.41	--	3.67	--	4.41	3.67
1995 total	--	24.19	--	--	--	--	33.33	--
1996								
January	--	8.88	6.96	--	4.09	--	6.96	4.09
February	--	2.42	1.07	26	4.99	--	2.42	4.99
March	--	4.59	0.28	21	6.21	--	4.59	6.21
April	--	1.08	1.19	--	6.56	--	1.19	6.56
May	--	0.61	0.48	29	6.39	29	0.61	6.83
June	--	4.15	3.70	--	4.59	19	3.70	7.25
July	--	1.98	1.54	--	4.78	21	1.54	7.06
August	--	1.94	1.93	--	7.15	--	1.93	7.15
September	--	3.34	3.25	--	5.83	--	3.25	5.83
October	--	1.47	1.59	28	5.92	28	1.59	6.55
November	22.1	15.33	0.00	1	0.14	1	15.33	[6]4.54
December	6.8	5.26	--	0	--	0	5.26	[6]4.25
1996 total	29.6	51.05	--	--	--	--	48.37	70.44
1997								
January	12.0	8.01	4.39	18	2.80	18	8.01	4.82
February	2.6	1.35	1.09	--	4.33	23	1.09	5.27
March	7.7	4.46	4.82	--	5.94	--	4.82	5.94
April	5.3	2.78	3.08	--	7.11	--	3.08	7.11
May	6.7	0.77	3.28	--	7.21	--	3.28	7.21
June	3.5	2.42	2.09	--	8.56	--	2.09	8.56
July	2.8	1.52	1.43	--	8.91	--	1.43	8.91
August	1.5	0.33	0.37	--	8.55	--	0.37	8.55
September	2.7	1.78	1.42	--	7.79	--	1.42	7.79
October	5.4	2.12	2.02	--	6.72	--	2.02	6.72
November	3.5	1.67	2.12	--	4.89	28	2.12	5.24
December	3.9	4.63	1.75	--	3.43	22	1.75	4.83
1997 total	56.9	31.84	27.86	--	76.24	--	31.48	80.95
November 1996–October 1997 total	78.7	46.13	--	--	--	--	48.20	78.80

[1] U.S. Fish and Wildlife Service meteorology station

[2] University of Hawaii meteorology station

[3] Number of days with records of rainfall or PE at station 10 for months having missing data

[4] A composite record using station 10 as the primary gage and substituting station 35 data where station 10 had missing data and less rain than station 35

[5] Computed by assigning the average observed daily rate for each month to missing days in that month

[6] Missing PE for November and December 1996 estimated by averaging values for the same months in 1995 and 1997

Table 15. End-of-month water levels in ponds at James Campbell National Wildlife Refuge, Oahu, Hawaii, December 1996 through December 1997

[Values in feet. Data from USFWS measurements at pond staff gages and from water-level recorders operated by USFWS and USGS; where measurements were not made on the ending day of the month, values were interpolated from the closest prior and subsequent dates]

Month	Kii ponds							Punamano north pond
	A	B	C	D	E	F	G	
December 1996	2.52	3.94	4.45	3.27	1.94	4.31	3.75	3.03
January 1997	2.73	3.98	4.46	3.26	3.08	4.35	3.75	2.98
February	2.14	3.99	4.33	3.25	1.74	4.26	3.71	2.07
March	2.20	3.90	4.35	3.24	1.70	4.30	3.70	2.54
April	1.95	3.93	4.21	3.25	1.34	4.23	3.66	2.29
May	1.86	3.92	4.20	3.26	1.08	4.22	3.66	2.33
June	1.60	3.82	4.08	3.24	0.90	4.18	3.60	2.42
July	1.60	3.68	3.90	3.10	0.92	4.10	3.40	2.57
August	1.18	3.70	3.76	2.89	1.03	3.97	3.14	2.60
September	[1]1.57	3.60	3.83	2.86	1.75	4.07	3.12	2.68
October	[1]2.15	3.85	3.82	3.08	1.29	4.11	3.54	2.61
November	[1]2.71	3.69	4.17	3.24	1.51	4.17	3.50	2.61
December	[1]2.94	3.63	4.19	3.25	3.05	4.21	3.61	2.62
Change during 1997	+0.42	-0.31	-0.26	-0.02	+1.11	-0.10	-0.14	-0.41

[1] Rising water levels in pond A from September through December corresponded with USFWS filling of pond A with water from the adjacent outer ditch.

At both units, changes in storage were computed using end-of-month water levels derived from USFWS readings at pond staff gages and data from water-level recorders operated by USFWS and USGS (table 15). In cases where measurements were not made on the ending day of the month, values were interpolated from the closest prior and subsequent dates.

Results of the Water Budgets

Monthly water budgets for calendar year 1997 are shown in table 16 for Punamano Unit ponds and wetlands and in table 17 for Kii Unit ponds.

At Punamano Unit, the atmospheric components (rainfall and evapotranspiration) were the dominant measured terms in the budget in most months and showed a large excess of evapotranspiration over rainfall (table 16). Only in January did rainfall exceed evapotranspiration. As a result, the inflow-minus-outflow subtotal was predominantly negative throughout the year and showed a strong seasonal cycle, with the largest negative values during the summer months. Subtracting the change-in-storage term (ΔStorage), the resulting values of the residual differ somewhat from the inflow-minus-outflow values, but the overall pattern of negative values persisted for much of the year, implying that large gains from ground water were necessary to keep up with the demands of evapotranspiration and maintain standing water in the marsh. The change-in-storage term was large in February, March, and April, reflecting the effects of storms. The residual during these months is more likely to include errors in the surface-water terms, making it difficult to interpret the residual strictly in terms of ground-water gains or losses.

On an annual basis at Punamano Unit, total inflow was 24.8 Mgal, total outflow was 66.3 Mgal, and the residual showed a -37.9 Mgal deficit. An annual gain from ground water equalling a water depth of 50.8 inches over the budget area is required to satisfy this deficit. Supporting evidence for such ground-water gain lies in the low specific conductance readings throughout the Punamano ponds, which are just slightly higher than the springs that feed them (table 11 and fig. 20), and in the relatively stable water level in Punamano north pond (table 15). These data verify that the natural supply of freshwater is adequate to keep pace with evapotranspiration and maintain low salinity and stable pond level.

At Kii Unit, evapotranspiration and inflow from the artesian wells were the largest terms in most months

Table 16. Monthly water budget for the Punamano Unit, James Campbell National Wildlife Refuge, Oahu, Hawaii, 1997

[Values in million gallons (Mgal) except where noted; Mgal/d, million gallons per day; the budget area covers 27.5 acres of ponds and wetlands shown in figure 2; e, estimated]

	Inflow			Outflow					
Month	Rainfall[1]	Stream inflow[2]	Total	Stream outflow[3]	Evapotrans-piration[1]	Total	Inflow minus outflow	Change in storage[4]	Residual
January	6.0	e0.4	6.4	2.0	3.6	5.6	0.8	-0.4	1.2
February	0.8	e0.1	0.9	0.5	3.9	4.4	-3.5	-8.2	4.7
March	3.6	e0.4	4.0	2.0	4.4	6.4	-2.4	4.2	-6.6
April	2.3	e0.2	2.5	1.0	5.3	6.3	-3.8	-2.2	-1.6
May	2.4	e0.1	2.5	0.4	5.4	5.8	-3.3	0.4	-3.7
June	1.6	e0.0	1.6	0.0	6.4	6.4	-4.8	0.8	-5.6
July	1.1	e0.0	1.1	0.0	6.7	6.7	-5.6	1.3	-6.9
August	0.3	e0.0	0.3	0.0	6.4	6.4	-6.1	0.3	-6.4
September	1.1	e0.0	1.1	0.0	5.8	5.8	-4.7	0.7	-5.4
October	1.5	e0.0	1.5	0.0	5.0	5.0	-3.5	-0.6	-2.9
November	1.6	e0.0	1.6	0.0	3.9	3.9	-2.3	0.0	-2.3
December	1.3	e0.0	1.3	0.0	3.6	3.6	-2.3	0.1	-2.4
Total	23.6	1.2	24.8	5.9	60.4	66.3	-41.5	-3.6	-37.9
Annual average									
Mgal/d	0.065	0.003	0.068	0.016	0.165	0.182	-0.114	-0.010	-0.104
Inches	31.6	1.6	33.2	7.9	80.9	88.8	-55.6	-4.8	-50.8

[1] Computed by multiplying the composite rainfall or full-month potential evaporation values from table 14 times the budget area
[2] Runoff from Punamano inland drainage area (1a in figure 5), estimated from station 1 discharge by area-weighted prorating
[3] Station 1 discharge from table 4
[4] Computed by applying differences in end-of-month water levels at Punamano north pond in table 15 to the budget area

Table 17. Monthly water budget for the Kii Uni, James Campbell National Wildlife Refuge, Oahu, Hawaii, 1997

[Values in millions of gallons except where noted; Mgal/d, million gallons per day; the budget area covers 65.7 acres of ponds that are supplied with artesian well water (ponds A through G, excluding pond E; figure 3]

	Inflow			Outflow			
Month	Rainfall[1]	Well water[2]	Total	Evapotrans-piration[1]	Inflow minus outflow	Change in storage[3]	Residual
January	14.3	12.2	26.5	8.6	17.9	1.6	16.3
February	1.9	11.5	13.4	9.4	4.0	-5.0	9.0
March	8.6	9.5	18.1	10.6	7.5	0.3	7.2
April	5.5	9.7	15.2	12.7	2.5	-2.5	5.0
May	5.9	10.2	16.1	12.9	3.2	-0.6	3.8
June	3.7	9.4	13.1	15.3	-2.2	-3.0	0.8
July	2.6	9.8	12.4	15.9	-3.5	-2.3	-1.2
August	0.7	9.7	10.4	15.3	-4.9	-5.0	0.1
September	2.5	9.4	11.9	13.9	-2.0	[4]0.0	[4]-2.0
October	3.6	9.8	13.4	12.0	1.4	[4]2.5	[4]-1.1
November	3.8	9.5	13.3	9.3	4.0	[4]1.4	[4]2.6
December	3.1	8.2	11.3	8.6	2.7	[4]0.3	[4]2.4
Total	56.2	118.9	175.1	144.5	30.6	12.3	42.9
Annual average							
Mgal/d	0.154	0.326	0.480	0.396	0.084	0.034	0.118
Inches	31.5	66.6	98.1	81.0	17.2	6.9	24.0

[1] Computed by multiplying the composite rainfall or full-month potential evaporation values from table 14 times the budget area
[2] Artesian flow from the Kii wells, metered by USFWS and pro-rated across months where meter readings did not coincide with the ending day of the month)
[3] Sum of changes in individual ponds, which were computed from end-of-month water levels (table 15) and pond areas (table 13)
[4] Computed assuming no change in storage in pond A from September through December, when rising water levels corresponded with USFWS filling of pond A with water from the adjacent outer ditch. The assumption of zero change in storage in pond A eliminates this known, but unmeasured, surface-water component from the budget

and rainfall was subordinate, except in January (table 17). In contrast to the Punamano Unit, the inflow-minus-outflow subtotal and the residual at Kii Unit showed large positive values in most months, indicating a surplus of inflow over outflow and requiring unaccounted-for losses by surface-water outflow and/or ground-water seepage. The dry summer months showed deficits in supply, denoted by the negative values of inflow-minus-outflow and change in storage. These values reflect the fact that rainfall and well supply did not keep pace with evapotranspiration during the summer. When changes in storage are accounted for, the residual for the summer months is not as strongly negative as the inflow-outflow term. The change-in-storage and residual terms are complicated somewhat by maintenance at the ponds from mid- to late-1997: the large negative value of change in storage in August was due mainly to the draining of pond A (the largest of the ponds), and refilling of pond A with outer ditch water from September through December further complicates the picture. The changes in storage associated with the refilling were left out of the change in storage term because the outer ditch water is a separate source of supply from the artesian wells and was not gaged.

On an annual basis at Kii Unit, total inflow was 175.1 Mgal, total outflow was 144.5 Mgal, and the residual showed a 42.9 Mgal surplus. The surplus represents an annual excess of inflow over outflow equalling 24.0 inches over the budget area, or 118,000 gal/d, which is equivalent to 36 percent of the average daily inflow from the artesian wells. The apparent surplus is strictly hydrologic, and is not a surplus in a management sense. That is, it is not a surplus that can be stored or used to supply the Refuge, but instead reflects losses from the system that render this amount of water unavailable for use. USFWS refuge managers state that there is not enough water to manipulate levels in the ponds for management purposes during most of the year, particularly during the driest months (M. Silbernagle, U.S. Fish and Wildlife Haleiwa, Hawaii, written commun., 1999). This contention is supported by the seasonal deficits shown in the budget, and may be true in other months despite apparent hydrologic surpluses in the budget.

The large apparent monthly and annual surpluses in supply at Kii Unit likely indicate unmeasured losses from the system. Two types of loss are most plausible: (1) surface-water loss by unmeasured tailwater discharge to the ditches through pond water-control structures; and (2) ground-water loss by downward and/or lateral seepage. Slight overflow at flashboards was observed at ponds D and G at Punamano ditch on several occasions in fair weather. How prevalent this overflow is or how much it might amount to is not known, but the largest overflows probably are during wet-season rainstorms. Refuge managers state that they try to maintain pond levels 1 to 2 inches below the flashboards (M. Silbernagle, USFWS Haleiwa Office, written commun., 1999). If pre-storm pond levels are this close to the tops of the flashboards, then several inches of rain on a single day could result in large unmeasured losses through the control structures. If this were to happen numerous times during the year, it might explain a substantial part of the apparent surplus in the Kii budget. Ground-water seepage losses are plausible given the downward head gradients observed at most of the piezometers, and given that pond levels are almost always higher than adjacent ditch levels. Despite the mud and clay composition of the pond bottoms and berms, the entire annual surplus of 24.0 inches over the area of the ponds could be disposed of at a seepage rate of only 0.07 in/d. Seepage this small would be difficult to measure using hydraulic approaches. Alternatives such as isotopic or other chemical analysis of pond waters and underlying ground water might be required to help verify and quantify such seepage.

A final possibility is that the residual components in the Punamano and Kii budgets result in part (or largely) from errors and imprecision in the measured or estimated budget components. The annual residual at Punamano Unit represents 42 percent of the total budget and at Kii Unit it represents 13 percent. At Punamano Unit, the surface-water inflow component was estimated, and therefore is uncertain. Furthermore, there may be additional surface-water inflows from lowlands surrounding Punamano marsh that were not accounted for. At Kii Unit, inflow from the artesian wells was recorded by totalizing flow meters, but the yield from each of the three wells was unequal, and there was some concern in 1998 as to whether all of the meters were functioning properly. Finally, errors in the rainfall and evapotranspiration measurements are possible, although the measurements were made using standard methods. Some error may have been introduced in estimating full-month values for months with several days of missing record.

Relation of the Budget Period to Long-Term Average Conditions

The 1997 rainfall of 31.48 inches (table 14) is considerably less than the long-term median annual rainfall (39.0 inches) and mean annual rainfall (41.5 inches) at nearby Kahuku Mill, equalling 81 percent and 76 percent of these values, respectively (Giambelluca and others, 1986; adjusted values for the long-term base period 1916–83 at Station 912.00). The annual potential evaporation of 80.95 inches for 1997 (table 14) is about the same as the 82.2 inches of mean annual pan evaporation reported for the coastal plain by Ekern and Chang (1985) for the period 1960–65, but a pan factor must be applied to pan evaporation values to approximate potential evaporation from open water bodies such as ponds or lakes. Applying the 0.8 factor recommended by Ekern and Chang (1985) for Hawaii results in a corresponding potential evaporation estimate of 65.8 inches. However, the 6-year time period of the pan evaporation data was wetter than normal and not entirely representative of long-term conditions (mean rainfall for 1960–65 was 49.1 inches, or 118 percent of the 41.5-inch long-term mean).

Judging from the comparisons above, 1997 was considerably drier than normal, about 24 percent below the long-term mean. A dry year would also be expected to be less cloudy than normal, which would help account for the measured 1997 potential evaporation being much greater than the estimate derived from Ekern and Chang's (1985) pan evaporation data, which was measured during a wetter-than-normal period.

WATER AND SEDIMENT QUALITY

An appraisal of water quality within the Refuge was undertaken as part of this study. Its objectives were to evaluate current conditions in the Refuge, to determine if any aspects of water quality within the Refuge pose a threat to wildlife health, and to create a baseline set of data for possible comparison with future surveys.

Samples of water and pond-bottom sediment were collected during two surveys, November–December 1994 and March 1997, representing dry- and wet-season conditions, respectively. Samples were analyzed for a suite of inorganic and organic chemical constituents and physical characteristics. The 1994 survey consisted of water samples from five sites and sediment samples from three sites (table 3 and fig. 6). The 1997 survey consisted of water samples from nine sites of which five were sampled during the 1994 survey.

Water and Sediment Sampling and Analysis

Water samples and pond-bottom sediments were collected from selected sites (figs. 6 through 9) for determining major constituents and a suite of trace substances (metals and organic compounds). Although definitions of the terms "major" and "trace" in reference to element concentrations are not precise, substances typically occurring in concentrations of less than 1,000 parts per million (less than 0.1 percent) are considered trace elements (Forstner and Willmann, 1979, p. 5). Elements typically occurring in concentrations of greater than 1,000 parts per million (ppm) are considered major elements.

Ultra-clean procedures (Horowitz and others, 1994) were used for collecting samples for inorganic analysis. Water samples from the Kii artesian wells were collected from the common well sump, using pre-cleaned Teflon bailers and with the wells actively flowing. Samples from the ponds were collected by dipping pre-cleaned high-density propylene 1-liter wide mouth bottles. Field measurements (temperature, specific conductance, pH, and dissolved oxygen) were made on the water samples, following standard USGS procedures (Wilde and others, 1998). Pond-bottom sediments were cored at selected sites (fig. 9) for mineralogic analysis and determination of inorganic and organic constituents as described by De Carlo and Spencer (1995). Where coring proved difficult, surface sediment was collected by scooping with a clean mason jar. All samples were stored on ice prior to analysis, and were shipped to the USGS National Water Quality Laboratory (NWQL) in Denver and the Department of Oceanography atomic spectroscopy facility at the University of Hawaii (UH) in Honolulu.

Inorganic analyses were made at the UH lab. Analysis of nutrients and organic constituents including pesticides and VOC's (volatile organic compounds) was made at the NWQL. The Quality Assurance and Quality Control (QA/QC) plan for the NWQL laboratory is described in Pritt and Raese (1995), whereas the QA/QC plan for the UH laboratory is available upon request (E.H. De Carlo, University of Hawaii, oral commun., 1997). The performance of each laboratory is monitored by semiannual participation in the USGS Standard Water Reference Sample Program.

Results

Inorganic Chemical Analysis

Results of inorganic analyses of sediments and water samples are given in tables 18 through 20. Quality assurance included analysis of a variety of quality control samples. For sediment the National Research Council of Canada standard reference sediment MESS-1 was analyzed concurrently with environmental samples to ascertain recovery of sample during sediment digestion procedures and the subsequent analysis. Observed concentrations generally agree well with certified values except for a high recovery of the trace element cobalt that is attributed to the combination of substantial background signal and a very low concentration of cobalt in this standard (table 18).

Duplicate water samples were collected to evaluate field variability and analytical reproducibility of analyses. Water samples E and J are duplicates from the composite Kii wells (tables 19 and 20). Major ion and alkalinity data for the duplicates are highly reproducible. Trace-element data show slightly more variability, especially for concentrations below 0.1 µg/L and approach instrument detection limits.

Inorganic Water Chemistry

No large variations in water major ion composition were noted between the 1994 (dry-season) and 1997 (wet-season) surveys (table 19), except for the calcium and alkalinity values in pond C. The nearly two-fold lower calcium and proportional decrease in alkalinity, but much less variable magnesium, sodium, and potassium concentrations between the two surveys may be attributable to precipitation of calcium carbonate within pond C.

The major ion composition of the Kii pond D (sample D in table 18) is best characterized as slightly brackish with a chloride concentration about 2 percent that of seawater. Concentrations of calcium, magnesium, sodium, potassium, chloride, and sulfate, the primary ions in seawater, are about 2 to 5 times higher in pond D than in water from the Kii artesian wells (samples E and J in table 19). The same element concentrations in Kii pond C (sample C in table 18) are comparable to or only slightly higher than those in the well water. Alkalinity is also about three-fold higher in pond D than in pond C or the wells. Concentrations of potassium and sulfate in pond D are nearly ten times higher than in pond C.

The major ion composition of Punamano pond (sample B in table 19) is roughly intermediate between that of pond C and pond D. Water in Punamano pond is only slightly saltier than that in Punamano Spring which ostensibly feeds it. The dissolved oxygen content of the pond water is rather low (45 percent saturation). Similarly low oxygen contents were observed in the 1997 (wet-season) samples collected from Kii ditch, from two sites on Hospital ditch, and from Punamano ditch at Nudist Camp Road (samples F, G, H, and I in table 19, respectively). Abundant algal mats and water hyacinth plants were observed at each of these sites.

The pH of all water ranges from a low of 6.95 in samples A and E to a high of 8.15 in sample D. The ponds having pH values in excess of 8 also exhibit higher calcium, magnesium, and alkalinity values than waters with lower pH.

Trace-element concentrations in waters (table 20) are generally low and in a range comparable to that reported for selected heavy metals in unimpacted or low-impact areas of Manoa Stream in the Ala Wai Canal Watershed on Oahu (De Carlo and others, 1997). Both dissolved (filtered) and total (unfiltered) concentrations of copper fall within the range of 0.4 to 8.2 µg/L compared with 0.1 to 7 µg/L for water from Manoa Stream. Zinc concentrations are between 0.5 and 8.9 µg/L. The high value of 8.9 µg/L observed in the filtered aliquot of pond D is approximately five-fold higher than observed in the unfiltered sample, suggesting a possible contamination of this sample during handling and processing. Elements such as aluminum, iron, and zinc typically display a high propensity for contamination of samples, owing to their high natural abundance in earth materials, their extensive use in domestic/industrial materials, and their ubiquitous presence in laboratory environments. Nonetheless, all zinc concentrations are well within the range observed in Manoa Stream (0.3 to 15 µg/L) by De Carlo and others (1997). All cadmium concentrations were less than 0.2 µg/L, in agreement with data for other freshwater samples collected on Oahu. Concentrations of lead ranged from 0.06 to 0.56 µg/L in samples collected in 1997. Higher values observed in the 1994 samples, particularly the 7 µg/L measured in the filtered aliquot of

Table 18. Major-element and trace-element composition of pond-bottom sediments, James Campbell National Wildlife Refuge, Hawaii, December 28, 1994 (dry season)

[Elements are listed by their chemical symbols; Bottom replicate, replicate sample from bottom of core; MESS-1 Found, determination run on National Research Council of Canada standard reference sediment designated MESS-1; MESS-1 Certif., certified value for MESS-1]

Element	Sample designation, station number, and location								MESS 1 Found	MESS 1 Certif.
	H, 44, Kii pond C		I, 12, Kii pond D			F and G, 36, Punamano pond				
	Top	Bottom	Top	Bottom	Bottom replicate	Top	Bottom	Bottom replicate		
Major elements (in weight-percent)										
Fe	11.2	11.6	11.9	12.2	11.9	2.96	3.22	3.33	3.01	3.05
Ca	0.74	0.99	3.43	5.10	4.87	7.79	9.01	9.52	0.48	0.48
Mg	0.50	0.67	0.85	0.81	0.71	0.87	1.14	1.17	0.81	0.87
Al	8.63	8.90	8.52	8.56	7.63	2.80	3.58	3.69	5.56	5.84
Si	18.2	18.3	13.0	14.8	13.8	20.2	21.3	20.2	31.7	31.3
P	0.22	0.22	0.22	0.20	0.20	0.20	0.21	0.21	0.07	0.06
Trace elements (in parts per million)										
Ti	1.83	1.73	1.68	1.67	1.52	0.27	0.31	0.32	0.42	0.54
Sr	76	82	195	251	242	305	419	429	87	89
Ba	62	61	71	74	81	33	39	49	321	[2]270
Cu	183	165	156	141	151	37	56	58	28	[2]25
Co	83	84	77	88	80	13	26	23	41	11
Mn	697	900	4,150	3,490	3,380	1,070	690	713	524	513
Ni	474	441	398	384	367	133	163	179	41	30
Zn	246	244	171	141	149	65	71	71	214	191
V	354	321	277	264	279	52	98	112	92	72
Pb	15	16	11	12	13	15	17	29	47	34
Cd	0.60	0.54	0.29	0.30	0.26	0.19	0.18	0.07	0.65	0.59

sample A (Punamano Spring) and the 9 µg/L in the unfiltered aliquot of sample C (Kii pond C) appear anomalously high, although they are close to the high end of the range reported for Manoa Stream (0.01 to 3 µg/L).

Concentrations of other trace elements presented in table 19 do not appear to display significant trends, except possibly arsenic, whose concentrations increased uniformly between the 1994 (dry-season) and 1997 (wet-season) surveys. A possible source of this element is fertilizers (association of arsenate with phosphate) or pesticides (for example, monomethyl arsenate). The occurrence of the highest concentrations of arsenic in samples G and H, collected within the Hospital ditch, suggests an input of this element from outside the Refuge. However, pond D also displayed elevated arsenic concentrations during both samplings (21 to 30.6 µg/L in filtered and unfiltered aliquots) whereas pond C did not (1.6 to 2.7 µg/L).

No significant contamination by heavy metals or other potentially toxic trace elements is apparent from the data in table 20, except as noted above for arsenic. Enhanced concentrations of iron and manganese observed in unfiltered water samples simply reflect inclusion of soil particles in the unfiltered water.

Inorganic Sediment Chemistry

The major element composition of the sediments (table 18) is consistent with the mineralogy described below. Sediment from Kii ponds C and D contain high concentrations of iron (11 to 12 percent), aluminum (8 to 9 percent), and silicate (13 to 18 percent) that are characteristic of local soils which contain red clay derived from weathering of volcanic minerals (De Carlo and Spencer, 1995). Ponds C and D differ significantly in their calcium and strontium contents, reflecting the presence of more marine minerals such as calcite (calcium carbonate) in pond D sediments. Other differences between the two ponds include higher concentrations of manganese in sediment from pond D, possibly resulting from redox reactions associated with the oxidation of organic matter. Higher concentration of solid phase manganese in surface sediments than in deep sediments

Table 19. Major-ion concentrations in surface and ground waters in the vicinity of James Campbell National Wildlife Refuge, Hawaii, November 22, 1994 (dry season) and March 13–14, 1997 (wet season)

[Alkalinity was determined from filtered, unacidified samples, but is listed here under the filtered, acidified category; µeq/L, microequivalents per liter; mg/L, milligrams per liter; °C, degrees Celsius; Alk, alkalinity; DO, dissolved oxygen, DOsat, dissolved oxygen saturation; Temp, water temperature; major ions are listed by their elemental symbols; --, not measured]

				Major ions							Field measurements			
Sample	Station[2]	Year	Alk (µeq/L)	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	Sr (mg/L)	K (mg/L)	[1]Cl (mg/L)	[1]SO_4 (mg/L)	pH	DO (mg/L)	DOsat (percent)	Temp (°C)
Filtered, acidified samples														
A	37	1994	2,560	56.5	31.0	112	0.297	2.37	--	--	6.95	5.9	--	23.0
A	37	1997	2,400	57.6	31.5	88.1	0.335	2.03	212	30	7.60	7.9	95	25.0
B	36	1994	2,490	61.5	35.5	126	0.387	4.23	--	--	7.10	5.1	--	23.0
B	36	1997	2,570	62.6	37.6	123.0	0.426	4.82	297	37	8.15	3.7	45	25.8
C	44	1994	1,540	44.5	30.5	85.5	0.295	4.21	--	--	7.55	6.2	--	24.5
C	44	1997	685	25.2	25.2	71.9	0.219	3.70	172	36	7.50	6.9	88	27.9
D	12	1994	5,570	97.0	70.5	267	0.844	25.6	--	--	8.35	6.6	--	23.0
D	12	1997	5,050	112	81.7	240	1.04	21.5	405	316	8.15	7.8	99	27.0
E	6	1994	1,560	36.0	22.4	57.0	0.217	2.09	--	--	6.95	7.6	--	22.0
E	6	1997	1,570	35.7	22.6	54.1	0.208	2.06	136	24	7.35	7.9	89	21.8
J	6	1997	1,570	35.1	22.4	53.2	0.204	2.06	139	18	7.35	7.9	89	21.8
F	3	1997	2,220	31.8	15.2	57.5	0.155	2.49	98	21	7.20	4.3	50	24.5
G	45	1997	3,420	47.4	23.5	73.8	0.354	3.88	115	27	7.25	3.7	46	24.5
H	4	1997	2,630	39.6	13.0	46.8	0.169	1.80	81	14	7.35	3.2	37	23.8
I	1	1997	1,750	38.3	20.8	82.4	0.204	1.12	178	22	7.05	1.7	20	25.8
Raw (unfiltered), acidified samples														
A	37	1994	--	53.0	30.9	104	0.302	2.30	242	35.8	--	--	--	--
A	37	1997	--	57.8	31.8	86.8	0.343	1.99	226	32	--	--	--	--
B	36	1994	--	57.5	34.5	114	0.376	4.24	287	38.5	--	--	--	--
B	36	1997	--	63.2	37.8	124	0.430	4.85	310	29	--	--	--	--
C	44	1994	--	43.2	30.0	90.5	0.280	4.19	229	41.5	--	--	--	--
C	44	1997	--	25.9	25.4	72.0	0.229	3.68	180	21	--	--	--	--
D	12	1994	--	98.0	73.0	252	0.824	24.4	413	236	--	--	--	--
D	12	1997	--	114	82.5	238	1.05	22.8	425	338	--	--	--	--
E	6	1994	--	35.5	22.5	54.0	0.204	2.13	145	23.7	--	--	--	--
E	6	1997	--	36.1	22.6	53.4	0.215	11.4	142	19	--	--	--	--
J	6	1997	--	35.6	22.2	53.2	0.211	2.05	137	20	--	--	--	--
F	3	1997	--	31.9	14.9	58.5	0.161	2.63	97	23	--	--	--	--
G	45	1997	--	48.0	23.4	75.2	0.357	3.93	133	26	--	--	--	--
H	4	1997	--	40.1	12.7	47.0	0.172	1.81	81	15	--	--	--	--
I	1	1997	--	39.0	20.8	82.2	0.210	2.28	173	24	--	--	--	--

[1] Cl and SO_4 analyzed only in unfiltered samples for dry season sampling

[2] Stations shown in figure 9

Table 20. Trace-element concentrations in surface and ground water near James Campbell National Wildlife Refuge, Hawaii, November 22, 1994 (dry season) and March 13–14, 1997 (wet season)

[Concentrations in micrograms per liter (µg/L); <, less than; determinations for November 1994 dry-season samples by GFAAS (Graphite Furnace Atomic Absorption Spectrometry) and hydride techniques (As, Hg, Se); determination for March 1997 wet-season samples by ICP-MS (Inductively Coupled Plasma Mass Spectrometry) and hydride techniques (Hg, Se); the trace elements are listed by their chemical symbols]

Sample	Station[1]	Year	Cr	Cu	Zn	Ag	Cd	Ba	Pb	Fe	Mn	As	Se	Hg
Filtered, acidified samples														
A	37	1994	3.4	1.2	<2	<0.1	0.03	9	7	<3	0.1	0.3	1.6	1.1
A	37	1997	2.1	0.8	2.4	0.09	0.11	8.1	0.09	4	4.5	0.5	1.4	0.2
B	36	1994	2.0	1.7	2.0	<0.1	0.04	4	2	16	1.6	2.1	1.8	0.0
B	36	1997	1.0	1.1	0.6	0.08	0.10	7.4	0.12	19	153	4.4	0.9	0.2
C	44	1994	2.1	4.6	<2	<0.1	0.17	4	2	13	13.2	2.6	2.3	0.2
C	44	1997	1.0	2.2	0.6	0.07	0.11	4.8	0.07	3	2.3	2.7	0.9	1.5
D	12	1994	1.7	3.7	<2	<0.1	0.07	10	2	10	41.7	27.0	2.8	0.0
D	12	1997	1.3	2.3	8.9	0.07	0.11	16.8	0.08	6	298	30.6	0.9	2.9
E	6	1994	3.6	1.4	2.0	<0.1	0.16	2	2	15	0.3	0.6	7.0	0.4
E	6	1997	2.4	0.5	<0.5	0.07	0.13	2.9	0.08	2	<0.1	<0.1	1.1	<0.07
J	6	1997	2.5	0.4	<0.5	0.07	0.09	3.0	0.06	4	1.5	<0.1	0.9	0.5
F	3	1997	1.6	1.7	1.8	0.06	0.09	14.2	0.10	135	184	0.7	1.2	0.3
G	45	1997	1.0	0.9	<0.5	0.07	0.09	14.1	0.06	13	273	35.2	0.9	<0.07
H	4	1997	1.5	0.6	<0.5	0.07	0.08	10.1	0.08	2	175	37.9	1.1	0.1
I	1	1997	1.2	0.7	<0.5	0.07	0.10	5.4	0.10	191	115	1.7	0.9	0.1
Raw (unfiltered), acidified samples														
A	37	1994	3.3	2.7	<2	<0.1	0.16	13	4	16	1.4	0.1	<0.1	0.3
A	37	1997	2.2	0.8	1.35	0.06	0.09	7.8	0.13	75	5.5	0.6	1.3	0.1
B	36	1994	2.2	3.0	2.0	<0.1	0.14	2	2	133	54.4	1.9	<0.1	<0.1
B	36	1997	1.2	1.2	1.38	0.06	0.09	7.5	0.23	128	176	4.5	1.1	0.6
C	44	1994	6.1	8.2	<2	<0.1	0.12	3	9	1,130	52.5	1.6	<0.1	<0.1
C	44	1997	3.2	3.9	2.70	0.07	0.10	5.9	0.35	965	44.5	2.4	0.8	0.6
D	12	1994	4.0	5.0	<2	<0.1	0.14	14	2	529	99.0	21.0	<0.1	0.5
D	12	1997	3.5	3.5	1.37	0.07	0.11	19.0	0.28	1,200	399	30.6	1.2	<0.07
E	6	1994	3.6	1.6	<2	<0.1	0.08	3	2	17	0.2	<0.1	<0.1	0.6
E	6	1997	2.4	0.4	<0.5	0.06	0.08	2.7	0.06	3	3.0	<0.1	1.4	0.8
J	6	1997	2.5	0.4	<0.5	0.07	0.09	2.7	0.09	<3	2.7	<0.1	1.0	0.4
F	3	1997	3.9	3.0	3.32	0.07	0.09	17.0	0.31	616	213	0.3	1.6	<0.07
G	45	1997	0.6	1.2	1.50	<0.05	<0.04	14.7	0.43	1,050	288	65.2	1.1	<0.07
H	4	1997	0.7	0.5	1.29	<0.05	<0.04	11.0	0.56	138	202	38.7	1.2	<0.07
I	1	1997	1.9	1.1	<0.5	0.08	0.11	5.7	0.25	988	115	3.4	1.2	<0.07

[1] Stations shown in figure 9

at pond D, which indicates a flux of dissolved manganese from deeper within the sediment column and reprecipitation of manganese oxide near the sediment/water interface, are consistent with this hypothesis.

Sediments from Punamano pond contain much lower concentrations of iron (3 percent) and aluminum (3 to 4 percent) and much higher calcium (8 to 9 percent) and silicate (20 to 21 percent) than either Kii pond C or D (table 17). These differences are attributable to the Punamano pond sediment containing less red clay, perhaps owing to a combination of ground-water inputs and effective filtering of terrigenous sediment runoff by the ample vegetation (reeds) in and around the pond. Plankton productivity and a pre-existing, reef-carbonate dominated bottom would also account for the increased silicate and calcium contents, respectively.

Trace-element concentrations in the Punamano and Kii sediments (table 18) are generally low and comparable to those observed in other Hawaiian sediments derived from volcanic soils (for example, De Carlo and Spencer, 1995; 1997). Metals such as cadmium, cobalt, copper, nickel, and zinc are enriched about four-fold in Kii Unit ponds relative to those in Punamano pond. This coincides with an approximately four-fold difference in the iron content of the sediments from the two Refuge units. The positive correlation of trace-element concentrations with iron indicates that most of the trace-element concentrations of the ponds can be accounted for by an input of natural soil-derived sediment. No significant anthropogenic input of heavy metals to these ponds is immediately evident. Although concentrations of cadmium track iron contents, the concentrations are about two to three-fold higher than reported in uncontaminated soils and sediments (Kabata-Pendias and Pendias, 1992; De Carlo and Spencer, 1995, 1997). The elevated cadmium concentration of these sediments could be derived from three principal sources: automobile tire wear, superphosphate fertilizers, and sewage (De Carlo and Spencer, 1995; McMurtry and others, 1995). The first source is unlikely as zinc concentrations should be elevated commensurately if automobile tire wear were responsible for elevated cadmium. The fertilizer and sewage sources are more likely, although there is no unequivocal evidence that either source has contributed to the cadmium concentration of these sediments.

Lead concentrations in sediment (table 18) are uniformly low (11 to 29 ppm) in all three ponds and display no correlation with iron concentration. The concentrations of this element are comparable to soils from several other locations in Hawaii (Li, 1996) although slightly greater than those observed in uncontaminated soils (Kabata-Pendias and Pendias, 1992). These observations suggest that lead input to the Kii and Punamano pond sediments is derived from aerosol deposition associated with tropospheric transport of Asian dust in addition to local volcanically derived material (Hoffman and others, 1972). Recent stable lead isotope work by Spencer and De Carlo (1997) has shown that a significant portion of the lead found outside of developed areas in Hawaii, such as in ridgetop soils and in suspended sediment in stream reaches within upper undeveloped areas of watersheds, exhibits a remote Asian dust signature. It is unlikely that Kahuku receives much anthropogenic lead associated with urbanization and heavy automobile traffic.

Organic Chemical Analysis

Results of analysis for organic chemical compounds are listed in tables 21 through 23 (at end of report). In addition to the Quality Assurance and Quality Control (QA/QC) safeguards practiced at the USGS lab, duplicate water samples also were collected from the composite Kii artesian wells (samples E and J, table 22) to evaluate field variability and analytical reproducibility of the analyses.

Organic and Nutrient Water Chemistry

Very few organic compounds were detected at even a trace level in water samples; most were not detected (tables 21 and 22). In the 1994 (dry-season) survey, trace concentrations of atrazine were detected in Kii ponds C and D, and in the Kii artesian wells. Atrazine is a triazine herbicide that has been used widely in sugarcane cultivation in Hawaii. Atrazine in the Kii artesian wells may date to when Kahuku Plantation was in operation (1971 and earlier), inferring long infiltration and travel times in the Koolau aquifer, most likely prolonged by residence in soil and saprolite of the uplands unsaturated zone. Traces of simazine also were found in Punamano pond, Kii ponds C and D, and the Kii artesian wells. Also detected in Punamano pond was a trace concentration of chorpyrifos, an organophosphate pesticide. In the 1997 (wet-season) survey, diazinon was detected at the minimum reporting level

(MRL) at Hospital ditch near Kamehameha Highway. Diazinon is an organophosphate pesticide used in the United States on a wide variety of agricultural crops, ornamentals, domestic animals, lawns, gardens, and household pests (Sittig, 1985). A trace concentration of trifluralin, a triazine herbicide, was detected at Punamano pond. Trifluralin, a di-nitro aniline compound, is a known carcinogen (Sittig, 1985).

The highest concentrations of nitrogen in the form of ammonia and organic nitrogen were observed in Punamano pond, Kii ponds C and D, and Kii ditch at station 3. These results likely reflect natural processes, including the decomposition of organic matter in the organic-rich pond sediments and, at Kii ditch, possibly the decomposition of vegetation in the stream channel or organic matter in ground water beneath the adjacent aquaculture ponds. In the 1997 (wet-season) survey, the highest concentrations of nitrogen in the form of nitrite and nitrate were at Punamano Spring, the Kii artesian wells, and Hospital ditch at station 4. Samples from these sites all contain direct or nearby discharge from the Koolau aquifer and so implicate a ground-water source for the nitrite and nitrate. Lesser concentrations of nitrite and nitrate were found in Punamano ditch at station 1, Kii ditch at station 3, and Hospital ditch at the Kii Unit fence. These may reflect dilution of Koolau aquifer water by ground-water seepage from the alluvial fans or uptake of nitrite/nitrate by vegetation along the ditches. Similarly, concentrations of nitrite and nitrate were below the minimum reporting limit at Kii ponds C and D, and at the minimum reporting limit at Punamano pond. The lack of any enrichment of these species indicates a more complete uptake of nitrite and nitrate by pond vegetation.

Organic Sediment Chemistry

A different suite of organic compounds was found in sediments compared to water samples (table 23). The organochlorine pesticide DDT and its breakdown products, DDD and DDE, were detected at or above the minimum reporting limit in surface grab-samples of bottom sediment from Kii ponds C and D, and in the lower part of a sediment core taken at Punamano pond. Trace concentrations of ametryn were detected at Kii pond C and in the lower part of the Punamano core. Trace concentrations of bromacil, carboxin, diphenamid, and simetryn were detected in the upper part of the Punamano core, and a trace of propachlor was detected at Kii pond D. The only volatile organic compound detected in any of the surveys was toluene, at 12 µg/kg, in sediment from Kii pond C.

Sediment Mineralogy

Identifications of mineral phases were based on peak comparison of sample X-ray diffraction (XRD) patterns with those in the Joint Committee for Powder Diffraction Studies (JCPDS). Identifications are qualitative, although abundance estimates of individual phases can be made on the basis of relative peak intensities.

The sediments collected from pond C in the Kii Unit are primarily fine-grained materials, containing a mixture of clay minerals (including kaolinite) and a variety of iron oxide minerals, derived from the weathering of volcanic material. Trace amounts of pyrite and quartz also were detected. The presence of pyrite indicates a low redox state in the sediments, which results from the oxidation of organic matter settling in the ponds. Quartz in these sediments is likely of aeolian origin, although a small contribution from hydrothermal/volcanic quartz cannot be entirely ruled out (Jackson and others, 1971). Surface sediments from this site are very similar in mineralogical composition to those found at depth, with the exception of trace amounts of most likely biogenic calcite occurring in the deeper sediments.

The mineralogy of sediments from pond D is similar to that of pond C. Notable exceptions include slightly greater abundances of calcite and pyrite, and the occurrence of traces of aragonite. Solely on the basis of peak intensities, the abundance of pyrite also appears greater in deeper sediments of pond D than in surface sediments. The increased abundance of pyrite and carbonate minerals in sediments of pond D may reflect a slightly greater biologic productivity and concomitant higher oxygen demand in this pond. Initial and subsequent examinations of the ponds consistently revealed a large difference in the color of the water of these two ponds. Pond D is generally clearer than pond C, which is characterized by a brownish color reminiscent of storm water with a high suspended solid load. The inorganic water chemistry of the two ponds discussed earlier in this report attests further to their difference.

Sediments collected from Punamano pond are generally similar to those from Kii ponds C and D, in that they consist mainly of clay minerals (including kaolinite) and iron oxide minerals derived from volcanic soil.

However, biogenic calcite is much more abundant in the Punamano pond sediments.

Comparison of Trace-Element and Organic Compound Concentrations in Water and Bottom Sediment with Water-Quality Guidelines

Concentrations of some trace elements and organic compounds increase through higher levels of the food chain. These increases in concentration can directly affect Refuge wildlife because these wildlife are high on the food chain. Studying the effects on wildlife of trace elements and organic compounds in water and pond-bottom sediments was beyond the scope of this study. The presence of trace elements and organic compounds in water and bottom sediments can be related to their adverse effects on aquatic communities.

Water

Trace-element and organic compound concentrations in filtered- and unfiltered-water samples collected as part of this study (tables 20, 21, and 22) were compared against U.S. Environmental Protection Agency ambient water-quality criteria for protection of aquatic life and human health (U.S. Environmental Protection Agency, 1986). All constituents analyzed were below these criteria except for copper in a sample collected from Kii Pond C during the 1994 (dry-season) survey. The copper concentration in this unfiltered sample was 8.2 μg/L (table 20), as compared to the aquatic life chronic criteria of 6.5 μg/L.

Pond-Bottom Sediment

The potential for adverse biological effects associated with contaminated sediment was assessed using interim sediment-quality guidelines [threshold effect level (TEL), and probable effect level (PEL)] for freshwater sediments (Canadian Council of Ministers of the Environment, 1999). Sediment chemical concentrations below the TELs are not expected to be associated with any adverse biological effects, while concentrations above the PELs are expected to be frequently associated with adverse biological effects. Chemical concentrations between the TELs and PELs represent the range in which effects are occasionally observed.

The National Status and Trends Program (NSTP) approach (Long and Morgan, 1990) with modifications was used to derive TEL and PEL values. This approach involves the evaluation and compilation of chemical and biological data from numerous studies (including models of equilibrium partitioning in sediments, sediment-quality assessments values, spiked sediment toxicity tests and field studies) conducted throughout North America. The available data covered a large and varied geographic area and included many different species and biological endpoints. However, it should be noted that the guidelines are not based on a toxicological response and do not directly infer a cause and effect relation among chemical concentrations in sediment and the uptake of these chemicals by aquatic organisms. As a result, the following screening for exceedance of these interim sediment-quality guidelines (PELs and TELs) should be used only to determine which chemicals and locations are likely to be associated with adverse biological effects. Site-specific biological assessments and other measures of biological effects should be used in conjunction with these numerical guidelines to support practical and informed decisions regarding sediment quality.

Trace-element and organic compound data from the Kii and Punamano Ponds (tables 18 and 23) were compared with the Canadian interim sediment-quality guidelines for freshwater sediments. Copper concentrations in sediments from Kii ponds C and D (141 to 183 ppm) exceeded the PEL and TEL guidelines (108 and 18.7 ppm, respectively), and zinc concentrations (141 to 246 ppm) exceeded the TEL guideline for zinc (124 ppm). In sediments from Punamano pond, copper concentrations (37 to 58 ppm) exceeded just the TEL guideline (18.7 ppm). Despite exceeding sediment-quality guidelines, copper and zinc are naturally abundant in Hawaiian volcanic soils, and concentrations in Refuge sediments were comparable to or only slightly higher than those of stream sediments near the head of Manoa Valley in Honolulu (copper 146 ppm, zinc 228 ppm; De Carlo and Spencer, 1995), which presumably have been little affected by anthropogenic sources. Therefore, anthropogenic sources of copper and zinc to the Refuge are not strongly indicated by the data, although there may have been some contribution from periodic flooding or from the pre-1971 use of the ponds for settling of sugarcane washing and processing waters. All other trace-element and organic compound concentrations were less than the sediment-quality guidelines for freshwater sediments.

SUMMARY AND CONCLUSIONS

A hydrologic investigation was done over the 16-month period November 1996 through February 1998 to identify and quantify principal inflows and outflows of water to and from the James Campbell National Wildlife Refuge, determine the adequacy of the current freshwater supply, identify hydraulic factors affecting flooding, document ground-water/surface-water interactions, and determine the water- and sediment quality.

Streamflow during the study was dominated by winter stormflows, followed by a gradual recession of flow into summer 1997 as water that had been stored in alluvial fans drained to lowland ditches. Ohia Ai Gulch accounted for 89 percent of upland runoff in 1997 owing to its large drainage basin which extends into the rainy uplands. Outflow at the ditch terminus in 1997 was 125 Mgal greater than measured inflow to the coastal plain, mainly reflecting gains from ground water along the ditches between outlying gages and the ditch terminus. In September 1997, measured inflow was almost negligible, yet the Kii outlet pump discharged 7.99 Mgal, most of which must have originated as ground-water discharge. Of the measured 1997 outflow, 98 percent was through the Kii outlet pump, with the outlet culvert valve only opening for brief periods during storms. Large volumes of stormflow escaped over the flood-relief swales unmeasured.

During the largest storm of the study, in November 1996, Kalaeokahipa Stream and Hospital ditch overtopped Kamehameha Highway, apparently due to exceedance of culvert capacity, though Kalaeokahipa bridge may have been partly obstructed by vegetation. Slight overbank flooding in Kii ditch resulted strictly from high discharge (no backwater effect was evident). Minor overbank flooding farther out on the coastal plain was likely caused principally by the small hydraulic gradients available to convey stormflows along the lowland ditches. Stormwaters flooded Kii ponds and flowed back upstream along Punamano ditch into Punamano marsh, introducing suspended sediment and possibly other contaminants to the Refuge. By analyzing records from nearby long-term stream-gaging stations, the November 1996 storm is estimated to have a flood frequency of about 3 to 4 years. Two smaller storms in January 1997 resulted in smaller flows and no overbank flooding. The Kii outlet pump ran continuously with no shutoff for 7 days during the November 1996 storm and for 1 to 2 days during the January 1997 storms. During all three storms, the outlet culvert valve opened and the inner ditches overtopped the flood-relief swales, allowing free outflow of water from the inner ditch.

Backwater effects hindered drainage during the January 1997 storms at Hospital ditch at Kamehameha Highway, and at Punamano ditch at Nudist Camp Road (where the backflow into Punamano marsh in November 1996 constituted an extreme backwater effect). A probable marine backwater effect was imposed at the ocean outlet ditch during the November 1996 storm through a combination of high spring tides and wave setup from large surf. Whether this backwater effect propagated upstream in the ditches to affect inland sites could not be determined conclusively. A sand plug may have built up in the ocean outlet channel before the November 1996 storm, but if so, it was probably washed out before or early in the storm, and was not present at the time of peak stage at inland sites. A season-long buildup of the sand plug in late 1997 was inferred from rising water levels in the outlet ditch. Seawater washes up the outlet channel or over the sand berm and into the outer ditch system on most high tides, and particularly during spring high tides.

Ponds and ditches of the Refuge and surrounding lowlands have mud- and clay-lined bottoms that form an effective confining unit and inhibit interaction with an underlying shallow limestone aquifer. Kii pond levels are higher than adjacent ditch levels and underlying ground-water levels, establishing lateral and downward head gradients that could foster seepage losses from the ponds. Regional ground-water discharge from the Koolau aquifer to the coastal lowlands must be large, but discharge was evident only at a few known springs, suggesting that seepage is pervasive but diffuse. A regional salinity survey detected concentrated freshwater discharge where ridges of Koolau Basalt extend beneath coastal-plain sediments near Punamano Unit and at the head of Hospital ditch, and also detected brackish ground-water discharge into Kii ditch downstream of Kamehameha Highway. Wastewater disposal from the sewage treatment plant adjoining Kii Unit poses little or no threat to Refuge habitat. Disposal is actually at six injection wells 0.45 mile away at Kahuku, and the wells inject into confined limestone aquifers that do not extend to Kii Unit.

The natural freshwater supply to Punamano Unit is adequate, judging from stable pond levels and low salinities there. A monthly water budget for Punamano showed an apparent annual deficit in water supply in 1997, requiring unmeasured ground-water gains equalling 50.8 inches of water over the Punamano ponds and wetlands. The freshwater supply to Kii Unit is inadequate according to Refuge managers, who state that there is not enough water to manipulate levels adequately in the ponds during most of the year, and particularly during the driest months. This is confirmed by monthly deficits in the water budget for the Kii ponds during summer months. However on an annual basis, the Kii budget showed a surplus in supply for 1997 equalling 24.0 inches of water over the ponds fed by the artesian wells. Unmeasured losses are required to explain the apparent surplus, such as discharge to the ditches through pond water-control structures and downward or lateral ground-water seepage. The apparent annual surplus at Kii is strictly hydrologic and is not a surplus in a management sense; it cannot be stored or used to supply the Refuge, but instead reflects losses from the system that render this amount of water unavailable for use. The budget year, 1997, was drier than normal (24 percent below long-term mean rainfall) and so the measured potential evaporation for 1997 is probably higher than the long-term mean.

Few metals or organic compounds of potential concern were detected in pond and ditch waters and in pond-bottom sediments. Detected pesticides were at trace levels or just above minimum reporting limits. Exceptions that exceeded sediment quality guidelines include copper and zinc in sediment from Kii ponds C and D, and copper in sediment from Punamano pond. All other elements and organic compounds were at concentrations less than the guidelines for freshwater sediments. Judging from these results, urban and agricultural runoff appear to have contributed little in the way of harmful metals or organic compounds to the Refuge, although the potential for such contribution remains in the form of periodic flooding of the ponds by ditch stormflows. Salinity was low throughout most Refuge waters, qualifying as fresh to slightly brackish and more than suitable for the environmental needs of Refuge fauna. Higher salinities have been observed in ditches during past periods of sugarcane cultivation and saltwater aquaculture, however. Resumption of saltwater aquaculture could raise ditch salinities if saltwater effluents are disposed directly into the ditches, as they were in the past.

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Table 21. Organic compounds and nutrients in surface and ground water near James Campbell National Wildlife Refuge, Hawaii, November 22, 1994 (dry season)

[--, compound not detected and can be considered to be less than the reporting limit; <, less than; trace, compound detected, but at concentration less than the reporting limit; mg/L, milligrams per liter; µg/L, micrograms per liter; n.a., not available (sample unintentionally destroyed); analyses were performed by the USGS National Water Quality Laboratory in Denver, Colorado]

Chemical constituent	Units	Sample designation, station number, location[1]					Minimum reporting limit
		A, 37, Punamano Spring	B, 36, Punamano pond	C, 44, Kii pond C	D, 12, Kii pond D	E, 6, Kii wells	
Nutrients (USGS schedule 9)							
Nitrogen, ammonia + organic nitrogen, as N	mg/L	--	.5	.9	1.7	--	< .2
Nitrogen, nitrite, as N	mg/L	--	--	--	--	--	< .01
Phosphorus, total, as P	mg/L	0.1	.08	.23	.24	.06	< .01
Chlorophenoxy acid herbicides, water (USGS schedule 1304)							
2,4-D	µg/L	--	--	--	--	--	< .01
2,4-Dp dichlorprop	µg/L	--	--	--	--	--	< .01
2,4,5-T	µg/L	--	--	--	--	--	< .01
Silvex	µg/L	--	--	--	--	--	< .01
Organophosphate pesticides, total in water (USGS schedule 1319)							
Chorpyrifos	µg/L	--	trace	--	--	--	< .01
DEF S,S,S-Tributylphosphorotrithioate	µg/L	--	--	--	--	--	< .01
Diazinon	µg/L	--	--	--	--	--	< .01
Disulfoton	µg/L	--	--	--	--	--	< .01
Ethion	µg/L	--	--	--	--	--	< .01
Malathion	µg/L	--	--	--	--	--	< .01
Parathion	µg/L	--	--	--	--	--	< .01
Parathion-methyl	µg/L	--	--	--	--	--	< .01
Phorate	µg/L	--	--	--	--	--	< .01
Trithion	µg/L	--	--	--	--	--	< .01
Organochlorine pesticides, total in water (USGS schedule 1324)							
Aldrin	µg/L	--	--	--	--	--	< .01
Chlordane	µg/L	--	--	--	--	--	< .1
Dieldrin	µg/L	--	--	--	--	--	< .01
Endosulfan	µg/L	--	--	--	--	--	< .01
Endrin	µg/L	--	--	--	--	--	< .01
Heptachlor	µg/L	--	--	--	--	--	< .01
Heptachlor epoxide	µg/L	--	--	--	--	--	< .01
Lindane	µg/L	--	--	--	--	--	< .01
p,p′-Methoxychlor	µg/L	--	--	--	--	--	< .01
Mirex	µg/L	--	--	--	--	--	< .01
Perthane	µg/L	--	--	--	--	--	< .1
Polychlorinated biphenyls	µg/L	--	--	--	--	--	< .1
Polychlorinated napthalenes	µg/L	--	--	--	--	--	< .1
p,p'-DDD	µg/L	--	--	--	--	--	< .01
p,p'-DDE	µg/L	--	--	--	--	--	< .01
p,p'-DDT	µg/L	--	--	--	--	--	< .01
Toxaphene	µg/L	--	--	--	--	--	< 1

Table 21. Organic compounds and nutrients in surface and ground water near James Campbell National Wildlife Refuge, Hawaii, November 22, 1994 (dry season)--Continued

[--, compound not detected and can be considered to be less than the reporting limit; <, less than; trace, compound detected, but at concentration less than the reporting limit; mg/L, milligrams per liter; µg/L, micrograms per liter; n.a., not available (sample unintentionally destroyed); analyses were performed by the USGS National Water Quality Laboratory in Denver, Colorado]

Chemical constituent	Units	Sample designation, station number, location[1]					Minimum reporting limit
		A, 37, Punamano Spring	B, 36, Punamano pond	C, 44, Kii pond C	D, 12, Kii pond D	E, 6, Kii wells	
Triazine herbicides, dissolved (USGS schedule 1379)							
Alachlor	µg/L	--	--	--	--	--	< .05
Ametryn	µg/L	--	--	--	--	--	< .05
Atrazine	µg/L	--	--	trace	trace	trace	< .05
Cyanazine	µg/L	--	--	--	--	--	< .2
Desethylatrazine	µg/L	--	--	--	--	--	< .05
Deisopropylatrazine	µg/L	--	--	--	--	--	< .05
Metolachlor	µg/L	--	--	--	--	--	< .05
Metribuzin	µg/L	--	--	--	--	--	< .05
Prometon	µg/L	--	--	--	--	--	< .05
Prometryn	µg/L	--	--	--	--	--	< .05
Propazine	µg/L	--	--	--	--	--	< .05
Simazine	µg/L	--	trace	trace	trace	trace	< .05
Volatile organic compounds (VOC's), water (USGS schedule 1380; USEPA method 524.2)							
1,1,1,2-Tetrachloroethane	µg/L	--	n.a.	--	--	--	< .2
1,1,1-Trichloroethane	µg/L	--	n.a.	--	--	--	< .2
1,1,2,2-Tetrachloroethane	µg/L	--	n.a.	--	--	--	< .2
1,1,2-Trichloroethane	µg/L	--	n.a.	--	--	--	< .2
1,1,2-Trichlorotrifluoroethane	µg/L	--	n.a.	--	--	--	< .2
1,1-Dichloroethane	µg/L	--	n.a.	--	--	--	< .2
1,1-Dichloroethylene (ethene)	µg/L	--	n.a.	--	--	--	< .2
1,1-Dichloropropene	µg/L	--	n.a.	--	--	--	< .2
1,2,3-Trichlorobenzene	µg/L	--	n.a.	--	--	--	< .2
1,2,3-Trichloropropane	µg/L	--	n.a.	--	--	--	< .2
1,2,4-Trichlorobenzene	µg/L	--	n.a.	--	--	--	< .2
1,2,4-Trimethylbenzene	µg/L	--	n.a.	--	--	--	< .2
1,2-Dibromo-3-chloropropane (DBCP)	µg/L	--	n.a.	--	--	--	< 1
1,2-Dibromoethane (EDB)	µg/L	--	n.a.	--	--	--	< .2
1,2-Dichlorobenzene	µg/L	--	n.a.	--	--	--	< .2
1,2-Dichloroethane	µg/L	--	n.a.	--	--	--	< .2
1,2-Dichloropropane	µg/L	--	n.a.	--	--	--	< .2
1,3,5-Trimethylbenzene	µg/L	--	n.a.	--	--	--	< .2
1,3-Dichlorobenzene	µg/L	--	n.a.	--	--	--	< .2
1,3-Dichloropropane	µg/L	--	n.a.	--	--	--	< .2
1,4-Dichlorobenzene	µg/L	--	n.a.	--	--	--	< .2
1-Chloro-4-methylbenzene (4-chlorotoluene)	µg/L	--	n.a.	--	--	--	< .2
2,2-Dichloropropane	µg/L	--	n.a.	--	--	--	< .2
2-Chloroethylvinylether	µg/L	--	n.a.	--	--	--	< 1
2-Chlorotoluene	µg/L	--	n.a.	--	--	--	< .2

Table 21. Organic compounds and nutrients in surface and ground water near James Campbell National Wildlife Refuge, Hawaii, November 22, 1994 (dry season)--Continued

[--, compound not detected and can be considered to be less than the reporting limit; <, less than; trace, compound detected, but at concentration less than the reporting limit; mg/L, milligrams per liter; µg/L, micrograms per liter; n.a., not available (sample unintentionally destroyed); analyses were performed by the USGS National Water Quality Laboratory in Denver, Colorado]

Chemical constituent	Units	Sample designation, station number, location[1] A, 37, Punamano Spring	B, 36, Punamano pond	C, 44, Kii pond C	D, 12, Kii pond D	E, 6, Kii wells	Minimum reporting limit
Volatile organic compounds (VOC's), water (USGS schedule 1380; USEPA method 524.2)--Continued							
4-Isopropyl-1-methylbenzene (p-isopropyltoluene)	µg/L	--	n.a.	--	--	--	< .2
Benzene	µg/L	--	n.a.	--	--	--	< .2
Bromobenzene	µg/L	--	n.a.	--	--	--	< .2
Bromochloromethane	µg/L	--	n.a.	--	--	--	< .2
Bromodichloromethane	µg/L	--	n.a.	--	--	--	< .2
Bromoform	µg/L	--	n.a.	--	--	--	< .2
Bromomethane	µg/L	--	n.a.	--	--	--	< 2
Butylbenzene (*N*-butylbenzene)	µg/L	--	n.a.	--	--	--	< .2
Chlorobenzene	µg/L	--	n.a.	--	--	--	< .2
Chloroethane	µg/L	--	n.a.	--	--	--	< 2
Chloroform	µg/L	--	n.a.	--	--	--	< .2
Chloromethane	µg/L	--	n.a.	--	--	--	< 2
cis-1,2-Dichloroethylene (ethene)	µg/L	--	n.a.	--	--	--	< .2
cis-1,3-Dichloropropene	µg/L	--	n.a.	--	--	--	< .2
Dibromochloromethane	µg/L	--	n.a.	--	--	--	< .2
Dibromomethane	µg/L	--	n.a.	--	--	--	< .2
Dichlorodifluoromethane	µg/L	--	n.a.	--	--	--	< 2
Dichloromethane	µg/L	--	n.a.	--	--	--	< .2
Ethylbenzene	µg/L	--	n.a.	--	--	--	< .2
Hexachlorobutadiene	µg/L	--	n.a.	--	--	--	< .2
Isopropylbenzene	µg/L	--	n.a.	--	--	--	< .2
Naphthalene	µg/L	--	n.a.	--	--	--	< .2
Propylbenzene	µg/L	--	n.a.	--	--	--	< .2
sec-Butylbenzene	µg/L	--	n.a.	--	--	--	< .2
Styrene	µg/L	--	n.a.	--	--	--	< .2
tert-Butyl methyl ether	µg/L	--	n.a.	--	--	--	< .2
tert-Butylbenzene	µg/L	--	n.a.	--	--	--	< .2
Tetrachloroethylene (ethene)	µg/L	--	n.a.	--	--	--	< .2
Tetrachloromethane (carbon tetrachloride)	µg/L	--	n.a.	--	--	--	< .2
Toluene	µg/L	--	n.a.	--	--	--	< .2
trans-1,2-Dichloroethylene (ethene)	µg/L	--	n.a.	--	--	--	< .2
trans-1,3-Dichloropropene	µg/L	--	n.a.	--	--	--	< .2
Trichloroethylene (ethene)	µg/L	--	n.a.	--	--	--	< .2
Trichlorofluoromethane	µg/L	--	n.a.	--	--	--	< .2
Vinyl chloride	µg/L	--	n.a.	--	--	--	< 2
Xylene (dimethylbenzene)	µg/L	--	n.a.	--	--	--	< .2

[1] Stations shown in figure 9

Table 22. Organic compounds and nutrients in surface and ground water near James Campbell National Wildlife Refuge, March 13–14, 1997 (wet season)

[--, compound not detected and can be considered to be "less than" the reporting limit; <, less than; trace, compound detected, but at concentration less than the reporting limit; mg/L, milligrams per liter; µg/L, micrograms per liter; analyses were performed by the USGS National Water Quality Laboratory in Denver, Colorado]

Chemical constituent	Units	Sample designation, station number, location[1]										Minimum reporting limit
		A, 37, Punamano Spring	B, 36, Punamano pond	C, 44, Kii pond C	D, 12, Kii pond D	E, 6, Kii wells	F, 3 Kii ditch	G, 45, Hospital ditch	H, 4, Kahuku storm drain	I, 1 Punamano ditch	J, 6, Kii wells duplicate	
Nutrients + microkjeldahl P (USGS schedule 116)												
Nitrogen, ammonia, as N	mg/L	--	.02	--	--	--	.05	--	--	.05	--	< .015
Nitrogen, ammonia + organic nitrogen, as N	mg/L	--	.04	.4	.7	--	.2	--	--	--	--	< .2
Nitrogen, nitrite, as N	mg/L	0.01	.02	.01	.02	.01	.02	.02	.02	.03	.01	< .01
Nitrogen, nitrite + nitrate, as N	mg/L	1.1	.05	--	--	.95	.22	.09	1.1	.35	.96	< .05
Phosphorus, phosphate, ortho-, as P	mg/L	.09	.12	--	.07	.05	--	.02	.11	.03	.05	< .01
Phosphorus, total, as P	mg/L	.1	.12	.05	.07	.01	--	.06	.09	.02	.02	< .01
Chlorophenoxy acid herbicides, water (USGS schedule 1304)												
2,4-D	µg/L	--	--	--	--	--	--	--	--	--	--	< .01
2,4-Dp dichlorprop	µg/L	--	--	--	--	--	--	--	--	--	--	< .01
2,4,5-T	µg/L	--	--	--	--	--	--	--	--	--	--	< .01
Silvex	µg/L	--	--	--	--	--	--	--	--	--	--	< .01
Organophosphate pesticides, total in water (USGS schedule 1319)												
Chorpyrifos	µg/L	--	--	--	--	--	--	--	--	--	--	< .01
DEF S,S,S-Tributylphosphorotrithioate	µg/L	--	--	--	--	--	--	--	--	--	--	< .01
Diazinon	µg/L	--	--	--	--	--	--	.01	--	--	--	< .01
Disulfoton	µg/L	--	--	--	--	--	--	--	--	--	--	< .01
Ethion	µg/L	--	--	--	--	--	--	--	--	--	--	< .01
Fonofos	µg/L	--	--	--	--	--	--	--	--	--	--	< .01
Malathion	µg/L	--	--	--	--	--	--	--	--	--	--	< .01
Parathion	µg/L	--	--	--	--	--	--	--	--	--	--	< .01
Parathion-methyl	µg/L	--	--	--	--	--	--	--	--	--	--	< .01
Phorate	µg/L	--	--	--	--	--	--	--	--	--	--	< .01
Trithion	µg/L	--	--	--	--	--	--	--	--	--	--	< .01
Organochlorine pesticides, total in water (USGS schedule 1324)												
Aldrin	µg/L	--	--	--	--	--	--	--	--	--	--	< .01
Chlordane	µg/L	--	--	--	--	--	--	--	--	--	--	< .1
Dieldrin	µg/L	--	--	--	--	--	--	--	--	--	--	< .01
Endosulfan	µg/L	--	--	--	--	--	--	--	--	--	--	< .01
Endrin	µg/L	--	--	--	--	--	--	--	--	--	--	< .01
Heptachlor	µg/L	--	--	--	--	--	--	--	--	--	--	< .01
Heptachlor epoxide	µg/L	--	--	--	--	--	--	--	--	--	--	< .01
Lindane	µg/L	--	--	--	--	--	--	--	--	--	--	< .01
p,p′-Methoxychlor	µg/L	--	--	--	--	--	--	--	--	--	--	< .01
Mirex	µg/L	--	--	--	--	--	--	--	--	--	--	< .01
Perthane	µg/L	--	--	--	--	--	--	--	--	--	--	< .1
Polychlorinated biphenyls	µg/L	--	--	--	--	--	--	--	--	--	--	< .1

Table 22. Organic compounds and nutrients in surface and ground water near James Campbell National Wildlife Refuge, March 13–14, 1997 (wet season)--Continued

[--, compound not detected and can be considered to be "less than" the reporting limit; <, less than; trace, compound detected, but at concentration less than the reporting limit; mg/L, milligrams per liter; µg/L, micrograms per liter; analyses were performed by the USGS National Water Quality Laboratory in Denver, Colorado]

Chemical constituent	Units	Sample designation, station number, location[1]										Minimum reporting limit
		A, 37, Punamano Spring	B, 36, Punamano pond	C, 44, Kii pond C	D, 12, Kii pond D	E, 6, Kii wells	F, 3 Kii ditch	G, 45, Hospital ditch	H, 4, Kahuku storm drain	I, 1 Punamano ditch	J, 6, Kii wells duplicate	
Organochlorine pesticides, total in water (USGS schedule 1324)--Continued												
Polychlorinated napthalenes	µg/L	--	--	--	--	--	--	--	--	--	--	< .1
p,p′-DDD	µg/L	--	--	--	--	--	--	--	--	--	--	< .01
p,p′-DDE	µg/L	--	--	--	--	--	--	--	--	--	--	< .01
p,p′-DDT	µg/L	--	--	--	--	--	--	--	--	--	--	< .01
Toxaphene	µg/L	--	--	--	--	--	--	--	--	--	--	< 1
Triazine herbicides, dissolved (USGS schedule 1379)												
Acetochlor	µg/L	--	--	--	--	--	--	--	--	--	--	< .05
Alachlor	µg/L	--	--	--	--	--	--	--	--	--	--	< .05
Ametryn	µg/L	--	--	--	--	--	--	--	--	--	--	< .05
Atrazine	µg/L	--	--	--	--	--	--	--	--	--	--	< .05
Bromacil	µg/L	--	--	--	--	--	--	--	--	--	--	< .05
Butachlor	µg/L	--	--	--	--	--	--	--	--	--	--	< .05
Butylate	µg/L	--	--	--	--	--	--	--	--	--	--	< .05
Carboxin	µg/L	--	--	--	--	--	--	--	--	--	--	< .05
Cyanazine	µg/L	--	--	--	--	--	--	--	--	--	--	< .2
Cycloate	µg/L	--	--	--	--	--	--	--	--	--	--	< .05
Desethylatrazine	µg/L	--	--	--	--	--	--	--	--	--	--	< .05
Desisopropylatrazine	µg/L	--	--	--	--	--	--	--	--	--	--	< .05
Diphenamid	µg/L	--	--	--	--	--	--	--	--	--	--	< .05
Hexazinone	µg/L	--	--	--	--	--	--	--	--	--	--	< .05
Metolachlor	µg/L	--	--	--	--	--	--	--	--	--	--	< .05
Metribuzin	µg/L	--	--	--	--	--	--	--	--	--	--	< .05
Prometon	µg/L	--	--	--	--	--	--	--	--	--	--	< .05
Prometryn	µg/L	--	--	--	--	--	--	--	--	--	--	< .05
Propachlor	µg/L	--	--	--	--	--	--	--	--	--	--	< .05
Propazine	µg/L	--	--	--	--	--	--	--	--	--	--	< .05
Simazine	µg/L	--	--	--	--	--	--	--	--	--	--	< .05
Simetryn	µg/L	--	--	--	--	--	--	--	--	--	--	< .05
Terbacil	µg/L	--	--	--	--	--	--	--	--	--	--	< .05
Trifluralin	µg/L	--	trace	--	--	--	--	--	--	--	--	< .05
Vernolate	µg/L	--	--	--	--	--	--	--	--	--	--	< .05
Volatile organic compounds (VOC's), water (USGS schedule 1380; USEPA method 524.2)												
1,1,1,2-Tetrachloroethane	µg/L	--	--	--	--	--	--	--	--	--	--	< .2
1,1,1-Trichloroethane	µg/L	--	--	--	--	--	--	--	--	--	--	< .2
1,1,2,2-Tetrachloroethane	µg/L	--	--	--	--	--	--	--	--	--	--	< .2
1,1,2-Trichloroethane	µg/L	--	--	--	--	--	--	--	--	--	--	< .2
1,1,2-Trichlorotrifluoroethane	µg/L	--	--	--	--	--	--	--	--	--	--	< .2

Table 22. Organic compounds and nutrients in surface and ground water near James Campbell National Wildlife Refuge, March 13–14, 1997 (wet season)--Continued

[--, compound not detected and can be considered to be "less than" the reporting limit; <, less than; trace, compound detected, but at concentration less than the reporting limit; mg/L, milligrams per liter; µg/L, micrograms per liter; analyses were performed by the USGS National Water Quality Laboratory in Denver, Colorado]

Chemical constituent	Units	Sample designation, station number, location[1]										Minimum reporting limit
		A, 37, Punamano Spring	B, 36, Punamano pond	C, 44, Kii pond C	D, 12, Kii pond D	E, 6, Kii wells	F, 3 Kii ditch	G, 45, Hospital ditch	H, 4, Kahuku storm drain	I, 1 Punamano ditch	J, 6, Kii wells duplicate	
Volatile organic compounds (VOC's), water (USGS schedule 1380; USEPA method 524.2)--Continued												
1,1-Dichloroethane	µg/L	--	--	--	--	--	--	--	--	--	--	< .2
1,1-Dichloroethylene (ethene)	µg/L	--	--	--	--	--	--	--	--	--	--	< .2
1,1-Dichloropropene	µg/L	--	--	--	--	--	--	--	--	--	--	< .2
1,2,3-Trichlorobenzene	µg/L	--	--	--	--	--	--	--	--	--	--	< .2
1,2,3-Trichloropropane	µg/L	--	--	--	--	--	--	--	--	--	--	< .2
1,2,4-Trichlorobenzene	µg/L	--	--	--	--	--	--	--	--	--	--	< .2
1,2,4-Trimethylbenzene	µg/L	--	--	--	--	--	--	--	--	--	--	< .2
1,2-Dibromo-3-chloropropane (DBCP)	µg/L	--	--	--	--	--	--	--	--	--	--	< 1
1,2-Dibromoethane (EDB)	µg/L	--	--	--	--	--	--	--	--	--	--	< .2
1,2-Dichlorobenzene	µg/L	--	--	--	--	--	--	--	--	--	--	< .2
1,2-Dichloroethane	µg/L	--	--	--	--	--	--	--	--	--	--	< .2
1,2-Dichloropropane	µg/L	--	--	--	--	--	--	--	--	--	--	< .2
1,3,5-Trimethylbenzene	µg/L	--	--	--	--	--	--	--	--	--	--	< .2
1,3-Dichlorobenzene	µg/L	--	--	--	--	--	--	--	--	--	--	< .2
1,3-Dichloropropane	µg/L	--	--	--	--	--	--	--	--	--	--	< .2
1,4-Dichlorobenzene	µg/L	--	--	--	--	--	--	--	--	--	--	< .2
1-Chloro-4-methylbenzene (4-chlorotoluene)	µg/L	--	--	--	--	--	--	--	--	--	--	< .2
2,2-Dichloropropane	µg/L	--	--	--	--	--	--	--	--	--	--	< .2
2-Chlorotoluene	µg/L	--	--	--	--	--	--	--	--	--	--	< .2
4-Isopropyl-1-methylbenzene (p-isopropyltoluene)	µg/L	--	--	--	--	--	--	--	--	--	--	< .2
Benzene	µg/L	--	--	--	--	--	--	--	--	--	--	< .2
Bromobenzene	µg/L	--	--	--	--	--	--	--	--	--	--	< .2
Bromochloromethane	µg/L	--	--	--	--	--	--	--	--	--	--	< .2
Bromodichloromethane	µg/L	--	--	--	--	--	--	--	--	--	--	< .2
Bromoform	µg/L	--	--	--	--	--	--	--	--	--	--	< .2
Bromomethane	µg/L	--	--	--	--	--	--	--	--	--	--	< .2
Butylbenzene (*N*-Butylbenzene)	µg/L	--	--	--	--	--	--	--	--	--	--	< .2
Chlorobenzene	µg/L	--	--	--	--	--	--	--	--	--	--	< .2
Chloroethane	µg/L	--	--	--	--	--	--	--	--	--	--	< .2
Chloroform	µg/L	--	--	--	--	--	--	--	--	--	--	< .2
Chloromethane	µg/L	--	--	--	--	--	--	--	--	--	--	< .2
cis-1,2-Dichloroethylene (ethene)	µg/L	--	--	--	--	--	--	--	--	--	--	< .2
cis-1,3-Dichloropropene	µg/L	--	--	--	--	--	--	--	--	--	--	< .2
Dibromochloromethane	µg/L	--	--	--	--	--	--	--	--	--	--	< .2
Dibromomethane	µg/L	--	--	--	--	--	--	--	--	--	--	< .2
Dichlorodifluoromethane	µg/L	--	--	--	--	--	--	--	--	--	--	< .2
Dichloromethane (methylene chloride)	µg/L	--	--	--	--	--	--	--	--	--	--	< .2
Ethylbenzene	µg/L	--	--	--	--	--	--	--	--	--	--	< .2
Hexachlorobutadiene	µg/L	--	--	--	--	--	--	--	--	--	--	< .2

Table 22. Organic compounds and nutrients in surface and ground water near James Campbell National Wildlife Refuge, March 13–14, 1997 (wet season)--Continued

[--, compound not detected and can be considered to be "less than" the reporting limit; <, less than; trace, compound detected, but at concentration less than the reporting limit; mg/L, milligrams per liter; µg/L, micrograms per liter; analyses were performed by the USGS National Water Quality Laboratory in Denver, Colorado]

		Sample designation, station number, location[1]										
Chemical constituent	**Units**	**A, 37, Punamano Spring**	**B, 36, Punamano pond**	**C, 44, Kii pond C**	**D, 12, Kii pond D**	**E, 6, Kii wells**	**F, 3 Kii ditch**	**G, 45, Hospital ditch**	**H, 4, Kahuku storm drain**	**I, 1 Punamano ditch**	**J, 6, Kii wells duplicate**	**Minimum reporting limit**
Volatile organic compounds (VOC's), water (USGS schedule 1380; USEPA method 524.2)--Continued												
Isopropylbenzene	µg/L	--	--	--	--	--	--	--	--	--	--	< .2
Naphthalene	µg/L	--	--	--	--	--	--	--	--	--	--	< .2
Propylbenzene	µg/L	--	--	--	--	--	--	--	--	--	--	< .2
sec-Butylbenzene	µg/L	--	--	--	--	--	--	--	--	--	--	< .2
Styrene	µg/L	--	--	--	--	--	--	--	--	--	--	< .2
tert-Butyl methyl ether (MTBE)	µg/L	--	--	--	--	--	--	--	--	--	--	< .2
tert-Butylbenzene	µg/L	--	--	--	--	--	--	--	--	--	--	< .2
Tetrachloroethylene (ethene)	µg/L	--	--	--	--	--	--	--	--	--	--	< .2
Tetrachloromethane (carbon tetrachloride)	µg/L	--	--	--	--	--	--	--	--	--	--	< .2
Toluene	µg/L	--	--	--	--	--	--	--	--	--	--	< .2
trans-1,2-Dichloroethylene (ethene)	µg/L	--	--	--	--	--	--	--	--	--	--	< .2
trans-1,3-Dichloropropene	µg/L	--	--	--	--	--	--	--	--	--	--	< .2
Trichloroethylene (ethene)	µg/L	--	--	--	--	--	--	--	--	--	--	< .2
Trichlorofluoromethane	µg/L	--	--	--	--	--	--	--	--	--	--	< .2
Vinyl chloride	µg/L	--	--	--	--	--	--	--	--	--	--	< .2
Xylene (dimethylbenzene)	µg/L	--	--	--	--	--	--	--	--	--	--	< .2

[1] Stations shown in figure 9

Table 23. Organic compounds in pond-bottom sediments at James Campbell National Wildlife Refuge, Oahu, Hawaii, December 28, 1994 (dry season)

[Reporting limits varied from sample to sample for some constituents; --, compound not detected and can be considered to be "less than" the reporting limit; <, less than; trace, compound detected, but at concentration less than the reporting limit; µg/kg, micrograms per kilogram; est., estimated; analyses were performed by the USGS National Water Quality Laboratory in Denver, Colorado; do., ditto]

Chemical constituent	Units	Sample designation				Minimum reporting limit				
							By individual sample			
		Punamano north pond (top of sediment core)	Punamano north pond (bottom of sediment core)	Kii pond C, grab sample (top of sediment)	Kii pond D, grab sample (top of sediment)	For all samples	Punamano north pond (top of sediment core)	Punamano north pond (bottom of sediment core)	Kii pond C, grab sample (top of sediment)	Kii pond C, grab sample (top of sediment)
Organophosphate pesticides, bottom material (USGS schedule 1320)										
Diazinon	µg/kg	--	--	--	--	<0 .2	--	--	--	< .4
Ethion	µg/kg	--	--	--	--	< .2	--	--	--	< .4
Malathion	µg/kg	--	--	--	--	< .2	--	--	--	< .4
Parathion	µg/kg	--	--	--	--	< .2	--	--	--	< .4
Parathion-methyl	µg/kg	--	--	--	--	< .2	--	--	--	< .4
Trithion	µg/kg	--	--	--	--	< .2	--	--	--	< .4
Organochlorine pesticides, bottom material (USGS schedule 1325)										
Aldrin	µg/kg	--	--	--	--	--	< .3	< .1	< .2	< .2
Chlordane	µg/kg	--	--	--	--	--	< 3	< 1	< 2	< 2
Dieldrin	µg/kg	--	--	--	--	--	< .3	< .1	< .2	< .2
Endosulfan	µg/kg	--	--	--	--	--	< .3	< .1	< .2	< .2
Endrin	µg/kg	--	--	--	--	--	< .3	< .1	< .2	< .2
Heptachlor	µg/kg	--	--	--	--	--	< .3	< .1	< .2	< .2
Heptachlor epoxide	µg/kg	--	--	--	--	--	< .3	< .1	< .2	< .2
Lindane	µg/kg	--	--	--	--	--	< .3	< .1	< .2	< .2
p,p′-Methoxychlor	µg/kg	--	--	--	--	--	< .3	< .1	< .2	< .2
Mirex	µg/kg	--	--	--	--	--	< .3	< .1	< .2	< .2
Perthane	µg/kg	--	--	--	--	--	< 3	< 1	< 2	< 2
Polychlorinated biphenyls	µg/kg	--	--	--	--	--	< 3	< 1	< 2	< 2
Polychlorinated napthalenes	µg/kg	--	--	--	--	--	< 3	< 1	< 2	< 2
p,p′-DDD	µg/kg	--	0.1	.3	.3	--	< .3	< .1	< .2	< .2
p,p′-DDE	µg/kg	--	.4	.7	.5	--	< .3	< .1	< .2	< .2
p,p′-DDT	µg/kg	--	--	.3	.2	--	< .3	< .1	< .2	< .2
Toxaphene	µg/kg	--	--	--	--	--	< 30	< 10	< 20	< 20
Triazine herbicides, dissolved (USGS schedule 1379)										
Alachlor	µg/kg	--	--	--	--	< .05	--	--	--	--
Ametryn	µg/kg	--	trace	trace	--	< .05	--	--	--	--
Atrazine	µg/kg	--	--	--	--	< .05	--	--	--	--
Cyanazine	µg/kg	--	--	--	--	< .2	--	--	--	--
Desethylatrazine	µg/kg	--	--	--	--	< .05	--	--	--	--
Deisopropylatrazine	µg/kg	--	--	--	--	< .05	--	--	--	--
Metolachlor	µg/kg	--	--	--	--	< .05	--	--	--	--
Metribuzin	µg/kg	--	--	--	--	< .05	--	--	--	--
Prometon	µg/kg	--	--	--	--	< .05	--	--	--	--
Prometryn	µg/kg	--	--	--	--	< .05	--	--	--	--
Propazine	µg/kg	--	--	--	--	< .05	--	--	--	--
Simazine	µg/kg	--	--	--	--	< .05	--	--	--	--
Bromacil	µg/kg	trace	--	--	--	limit not stated; trace est. < .01	--	--	--	--
Carboxin	µg/kg	trace	--	--	--	do.	--	--	--	--
Diphenamid	µg/kg	trace	--	--	--	do.	--	--	--	--
Propachlor	µg/kg	--	--	--	trace	do.	--	--	--	--
Simetryn	µg/kg	trace	--	--	--	do.	--	--	--	--

Table 23. Organic compounds in pond-bottom sediments at James Campbell National Wildlife Refuge, Oahu, Hawaii, December 28, 1994 (dry season)--Continued

[Reporting limits varied from sample to sample for some constituents; --, compound not detected and can be considered to be "less than" the reporting limit; <, less than; trace, compound detected, but at concentration less than the reporting limit; µg/kg, micrograms per kilogram; est., estimated; analyses were performed by the USGS National Water Quality Laboratory in Denver, Colorado; do., ditto]

Chemical constituent	Units	Sample designation: Punamano north pond (top of sediment core)	Sample designation: Punamano north pond (bottom of sediment core)	Sample designation: Kii pond C, grab sample (top of sediment)	Sample designation: Kii pond D, grab sample (top of sediment)	Minimum reporting limit: For all samples	By individual sample: Punamano north pond (top of sediment core)	By individual sample: Punamano north pond (bottom of sediment core)	By individual sample: Kii pond C, grab sample (top of sediment)	By individual sample: Kii pond C, grab sample (top of sediment)
Volatile organic compounds (VOC's), bottom material (custom analysis, USGS laboratory)										
1,2-Dibromoethane	µg/kg	--	--	--	--	< 1	--	--	--	--
1,2,3-Trichloropropane	µg/kg	--	--	--	--	< 1	--	--	--	--
1,2-Dibromo-3-chloro-propane	µg/kg	--	--	--	--	< 1	--	--	--	--
Benzene	µg/kg	--	--	--	--		< 2.3	< 1.3	< 2	< 2.4
Bromoform	µg/kg	--	--	--	--	< 1	--	--	--	--
Bromodichloromethane	µg/kg	--	--	--	--	< 1	--	--	--	--
Chloroform	µg/kg	--	--	--	--	< 1	--	--	--	--
Dibromochloromethane	µg/kg	--	--	--	--	< 1	--	--	--	--
Ethylbenzene	µg/kg	--	--	--	--	< 1	--	--	--	--
Toluene	µg/kg	--	--	12	--	< 1	< 4	--	--	< 3
Xylene	µg/kg	--	--	--	--	--	< 1.7	< 1.2	< 1.7	< 2.2

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