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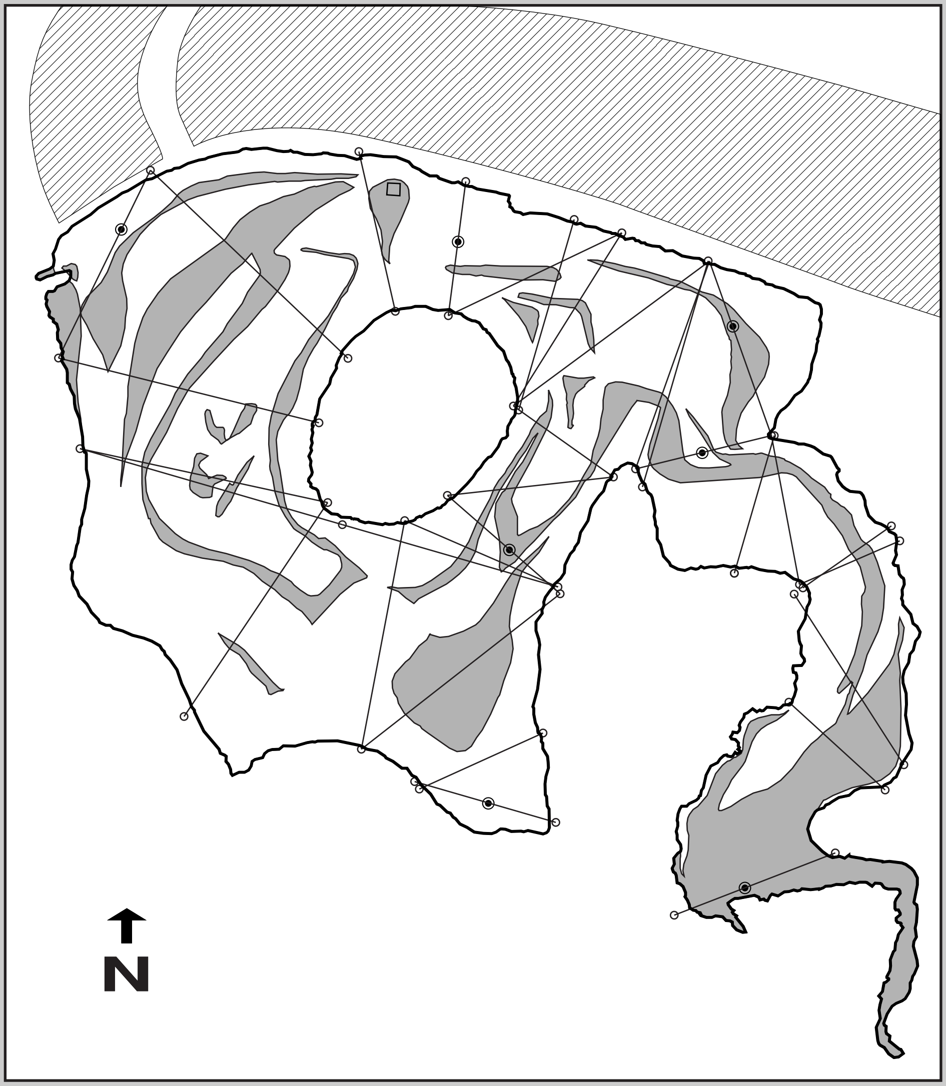
Sedimentation History of Waimaluhia Reservoir during Highway Construction, Oahu, Hawaii, 1983-98

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

Water-Resources Investigations Report 01-4001



Prepared in Cooperation with the
STATE OF HAWAII DEPARTMENT OF TRANSPORTATION
and the FEDERAL HIGHWAY ADMINISTRATION

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Honolulu, Hawaii
2001

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

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CONVERSION FACTORS

Multiply	By	To obtain
	Length	
inch (in)	2.54	centimeter
foot (ft)	0.3048	meter
	Area	
acres	4,047	square meter
square mile (mi^2)	2.590	square kilometer
square mile (mi^2)	640	acres
	Volume	
acre-foot (acre-ft)	1,233	cubic meter
	Volume per unit time (includes flow)	
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
cubic foot per second-days (ft^3/s-days)	0.02832	cubic meter per second-days
cubic foot per second-days per year (ft^3/s-days/yr)	0.02832	cubic meter per second-days per year
gallon per minute (gal/min)	0.06308	liter per second
million gallons per day (Mgal/d)	0.04381	cubic meter per second
	Density	
pound per cubic foot (lb/ft^3)	16.02	kilogram per cubic meter
pound per cubic foot (lb/ft^3)	0.016	grams per cubic centimeter
	Weight	
ton (ton)	0.9072	metric ton
ton per square mile per year ($ton/mi^2/yr$)	0.3503	metric ton per square kilometer per year

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

$$°C=(°F-32)/1.8$$

Sedimentation History of Waimaluhia Reservoir during Highway Construction, Oahu, Hawaii, 1983–98

By Michael F. Wong

Abstract

Nine sedimentation surveys conducted from 1983 to 1998 at Waimaluhia Reservoir determined the rate of sediment accumulation in the reservoir during H-3 Highway construction upstream of the reservoir. Rates of storage-capacity loss ranged from 1.1 acre-feet per year between 1983 and 1988 to 4.9 acre-feet per year between 1988 and 1992. The average loss rate during the period of intensive construction between 1983 to 1992 was 2.7 acre-ft per year. The average loss rate during the study period between 1983 and 1998 equals the design loss rate of 2.0 acre-feet per year. The average bulk density of deposited sediments was 29 pounds per cubic foot. From the bulk density data, loss of storage capacity, and suspended-sediment data collected downstream of the reservoir, a total of 26,950 tons of sediment was delivered to the reservoir from 1983 to 1998, of which 19,100 tons were trapped in the reservoir. From these sediment loads, a sediment yield of 565 tons per square mile per year and trap efficiency of 71 percent were computed. A trap efficiency of 60 percent, bulk density of 65 pounds per cubic foot, and sediment yield of 1,500 tons per square mile per year were used to compute the design loss rate of 2.0 acre-feet per year.

INTRODUCTION

Waimaluhia Reservoir is located within the Kamooalii Stream drainage basin on the eastern part of the island of Oahu (fig. 1). The reservoir was designed and constructed as part of the U.S. Army Corps of Engineers Kaneohe-Kailua Flood Control Project in response to heavy flooding in Kaneohe during the 1960's. Construction of the earth-fill dam started in 1977 and was completed in 1980. The reservoir was impounded in October 1980. Built at the former confluence of Kuou and Kamooalii Streams, Waimaluhia Reservoir was designed to maintain a constant pool altitude of 160 ft above mean sea level via an outlet structure in the pool, allowing a 50 percent turnover of water in the reservoir each week (U.S. Army Corps of Engineers, Honolulu District, 1981). The reservoir pool is part of a larger flood control reservoir. The main dam (fig. 2) with crest altitude of 222 ft is designed to retain a maximum flood stage of 217 ft. A spillway on the western end of the dam (fig. 2) becomes effective at flood altitudes over 202 ft. At maximum flood stage, the reservoir pool would cover 152 acres and hold 3,800 acre-ft of water (U.S. Army Corps of Engineers, Honolulu District, 1981). The H-3 Highway was constructed upstream of the reservoir between 1983 and 1998. Because the highway construction involved substantial disturbance of the land surface, concerns were raised over accelerated erosion from the construction and subsequent deposition in the reservoir, which potentially could deplete the storage capacity faster than the design loss rate of 2 acre-ft/yr. To assess the impact of the highway construction on the reservoir, the U.S. Geological Survey in cooperation with the State of Hawaii Department of Transportation and the Federal Highway Administration, conducted a number of bathymetric surveys of Waimaluhia Reservoir.

Purpose and Scope

The purpose of this report is to document rates of observed sediment deposition in Waimaluhia Reservoir during construction of the H-3 Highway. This report

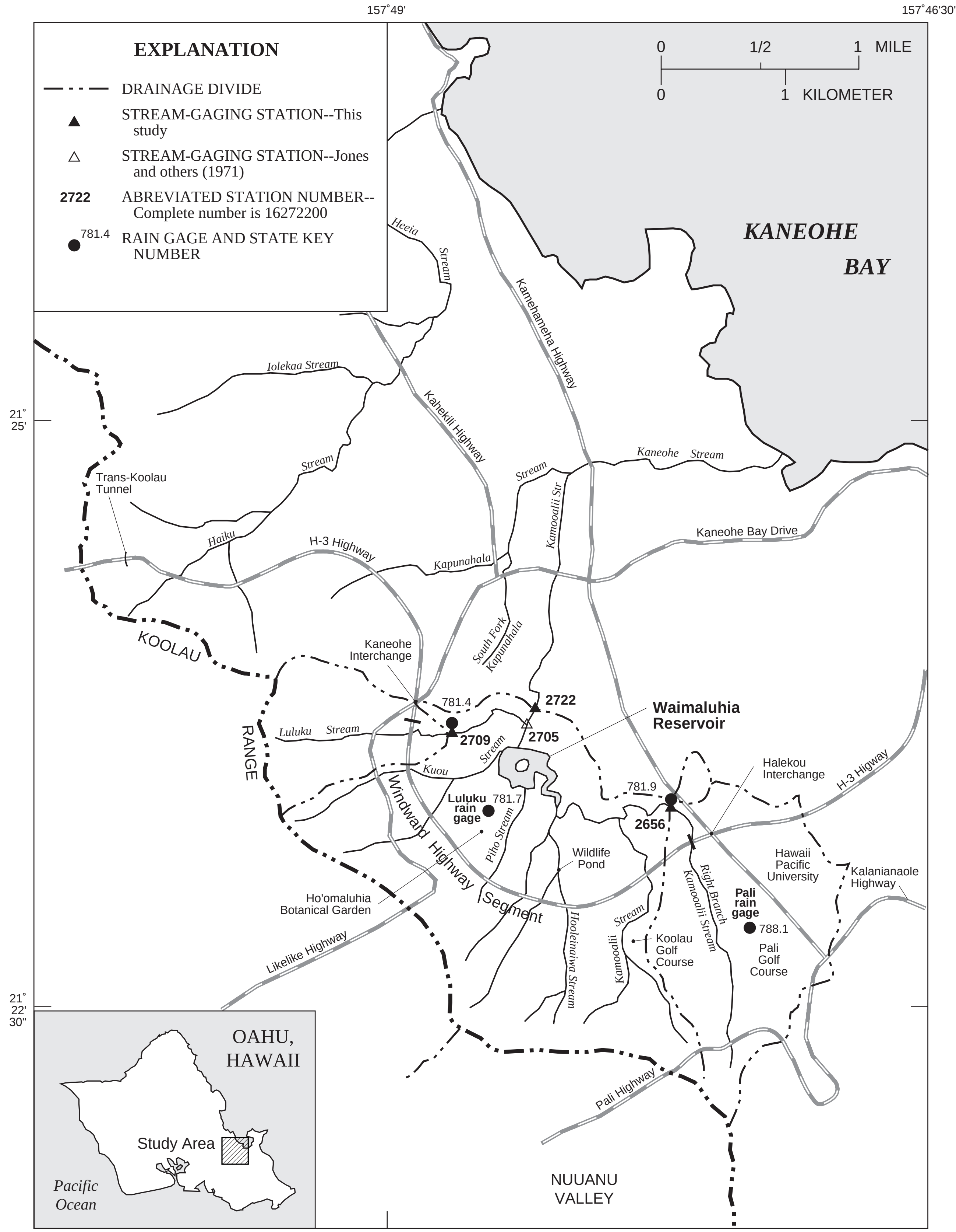

Figure 1. Waimaluhia Reservoir and study area, Oahu, Hawaii.

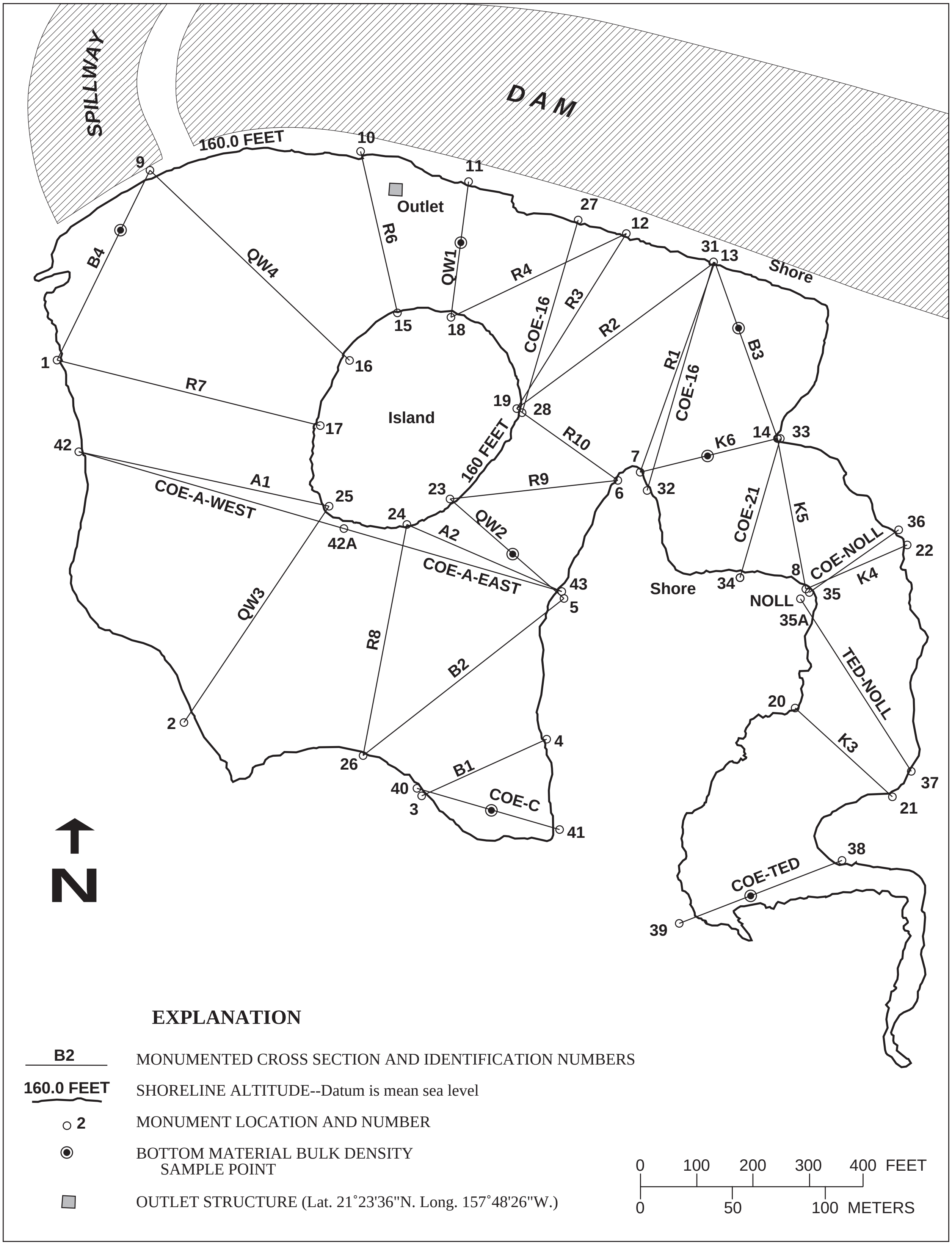

Figure 2. Monumented cross-section locations and reservoir bottom sample locations for the sedimentation survey of Waimaluhia Reservoir, Oahu, Hawaii.

describes the volume, mass, and distribution of sediments deposited in Waimaluhia Reservoir between 1983 and 1998 as calculated from bathymetric surveys, bottom sediment sampling, and suspended-sediment data.

Acknowledgements

The staff at the Ho'omaluhia Botanical Garden, Department of Parks and Recreation, City and County of Honolulu allowed access to Waimaluhia Reservoir and provided the boats used for field data collection. Dr. Eric DeCarlo, University of Hawaii at Manoa, provided the core sampler.

DESCRIPTION OF THE STUDY AREA

The Waimaluhia Reservoir drainage basin originates on the precipitous windward slopes of the Koolau Range. Elevations within the 3.20 mi^2 basin range from about 2,750 ft at the crest of the Koolau Range, to about 150 ft near the reservoir dam site. Stream-gaging station 2722 (fig. 1) is downstream of the dam, at an altitude of 116 ft, with a drainage area of 3.81 mi^2. (Four-digit gaging station numbers used in this report are abbreviated numbers. The complete numbers are preceded by 16 and end in 00. For example, for station 2722 the complete number is 16272200.) Because the dam was constructed upstream of the confluence of Luluku and Kamooalii Streams, streamflow at station 2722 includes water flowing through Waimaluhia Reservoir and water from perennial Luluku Stream that does not pass through the reservoir. The 0.61 mi^2 of area below the reservoir and upstream of station 2722 contains the 0.44 mi^2 Luluku basin upstream of station 2709 (fig. 1). Five tributaries flow into the reservoir. The smaller two, Kuou Stream and Piho Stream are intermittent (fig. 1) whereas, Hooleinaiwa, Kamooalii, and Right Branch Kamooalii Streams are perennial. Both Hooleinaiwa and Right Branch Kamooalii Streams flow into Kamooalii Stream upstream of the reservoir (fig. 1). Of these tributaries, only Right Branch Kamooalii Stream was continuously gaged at station 2656 (fig. 1).

The stream channels within these basins cut into bedrock in the steep cliff areas and into 2 to 20 ft of alluvium in the lower areas. Stream bed material consists of primarily small boulders, cobbles, and gravel intermixed with finer sediment, intermixed with a few large boulders. Alluvium, which underlies most of the drainage area, begins at about altitude 600 ft and extends down to sea level. Areas above 600 ft consist of the steep, volcanic rock cliffs of the Koolau Basalt. Areas to the east of the reservoir consist of the younger Honolulu Volcanics (geology from Takasaki and others, 1969; geologic names from Langenheim and Clague, 1987). Borings done by the U.S. Army Corps of Engineers (1975a) around the reservoir and dam site show the alluvium to be about 20 to 50 ft thick above volcanic tuff deposits. Basalt was encountered about 10 to 70 ft below the tuff in holes drilled near altitudes 120 to 140 ft (U.S. Army Corps of Engineers, 1975a).

Hydrology

The average annual temperature ranges from 74 to 76°F with diurnal temperature fluctuations of 8 to 10°F within the study area (Blumenstock and Price, 1961). The mean annual pan evaporation is about 50 in. (Ekern and Chang, 1985) and the median annual rainfall varies from about 59 in. near the coast to about 100 in. near the crest of the Koolau Range (State of Hawaii, 1982). The rainfall distribution is affected by the prevailing northeasterly winds and by the orographic lifting and cooling which results in heavier and more frequent rainfall near the Koolau Range crest. Annual rainfall totals by water year for four rain gages in the study area (fig. 1) are shown in table 1. Compared to 1983–98 average rainfall, 1988–89 and 1996–97 were relatively wet, whereas 1984, 1992, 1995, and 1998 were relatively dry. The average of the two Luluku rain gages (781.11 and 781.7) near the reservoir, which is about 75 in/yr (table 1), represents the mean annual rainfall on the reservoir.

Three continuous streamflow-gaging stations were operated during the study period. Station 2656, Right Branch Kamooalii Stream, upstream of the Waimaluhia Reservoir; station 2722, Kamooalii Stream below Luluku Stream, downstream of the reservoir; and station 2709, Luluku Stream at altitude 220 ft, measuring flow entering Kamooalii Stream downstream of the reservoir and upstream of station 2722 (fig. 1). Streamflow data collection at station 2722 started in November 1976 and continues to date (2000), while suspended-sediment data collection started on November 1976 and ended in September 1998. Streamflow and suspended-sediment data were collected from February 1983 to September 1997 at station 2656 and from April 1984 to June 1998 at station 2709. Annual streamflow totals in

Table 1. Annual rainfall in the Kamooalii Stream drainage basin, Oahu, Hawaii, water years 1981–98

[Numbers below gage names are State Key Numbers assigned to rain gages in Hawaii by the Commision of Water Resources Management, Department of Land and Natural Resources, State of Hawaii; all rainfall totals are in inches; --, no data; P, partial year, more than one month of missing data; e, estimated annual total, one or more months were estimated, value was estimated by comparison with other gages in the table]

	U.S. Geological Survey gages		National Weather Service gages	
Water Year	Luluku Stream (781.11)	Right Branch Kamooalii Stream (781.9)	Luluku (781.7)	Pali Golf Course (788.1)
1981	--	--	P	66.5
1982	--	--	P	127
1983	--	P	P	59.4
1984	P	38.9	41.9	37.8
1985	66.8	63.9	71.2	55.8
1986	66.2	59.2	74.2	53.3
1987	66.7	67.2	e76.1	62.5
1988	95.1	86.8	98.7	130
1989	87.2	84.1	e110	103
1990	62.8	62.4	e80.8	P
1991	64.9	68.5	P	80.1
1992	e55.9	42.2	e75.9	50.1
1993	61.6	P	76.2	110
1994	71.2	P	91.5	84.6
1995	49.1	e40.2	P	68.8
1996	73.7	e60.1	92.4	97.2
1997	e81.5	e75.9	e105	109
1998	44.7	P	P	40.7
Average[1]	67.7	62.4	82.8	78.6

[1] Only for complete years for the period 1981–98

cubic feet per second-days are listed by water year in table 2. Correlating with the rainfall data presented in table 1, 1984–85, 1992, 1995, and 1998 were years of low streamflow, whereas 1982, 1988–89, 1991, and 1997 were years of high streamflow (table 2). The flow through the reservoir can be computed as streamflow at station 2722 less streamflow at station 2709 (table 2). The average reservoir outflow computed in this manner for water years 1985–97 was 3,600 ft^3/s-days/year.

Perennial streamflow for most streams in the study area begins near altitude 550 ft and increases downstream to altitude 150 ft, with most of the gain between altitudes 225 and 150 ft (Takasaki and others, 1969). Streamflow gains downstream of station 2709 and upstream of Kamooalii Stream were insignificant, only 0.03 ft^3/s (Hill and others, 2000). No basal ground water was encountered in the 58 borings, the deepest reaching altitude 35 ft, drilled around the dam and reservoir site by the U.S. Army Corps of Engineers (1975a). Seepage of about 1 gal/min from coarse-grained alluvium was encountered in only four holes at altitudes of 120 to 140 ft. Thus, seepage into the reservoir is probably small and would occur near the Kamooalii Stream entrance to the reservoir since both Kuou and Piho Streams have been observed to go dry. Seepage on the downstream side of the earthen dam was observed during this study to be insignificant, not more than 0.03 ft^3/s, and what seepage was observed flowed into Kamooalii Stream upstream of station 2722.

Several municipal wells and a water tunnel are upstream of station 2722. Additional municipal and private wells and were drilled in the study area during this study. Average yearly pumpage from the municipal wells and tunnel from 1983 to 1996 was about 3 to 4 Mgal/d (data from Honolulu Board of Water Supply annual reports, 1983–96) while average yearly pumpage (1990–97) from the golf course wells is low, about 0.15 Mgal/d (data from Neal Fujii, Commission on Water Resource Management, Department of Land and Natural Resources, State of Hawaii, written commun.,

Table 2. Annual streamflow at stream-gaging stations in the Kamooalii Stream drainage basin, Oahu, Hawaii, water years 1981–98

[Values in cubic feet per second-days; --, no data; P, partial year, more than one month of no data; complete station numbers are preceded by 16 and end in 00]

Water Year	Station 2656 Right Branch Kamooalii Stream	Station 2722 Kamooalii Stream	Station 2709 Luluku Stream	Reservoir outflow, Kamooalii Stream less Luluku Stream
1981	--	3,140	--	--
1982	--	8,040	--	--
1983	P	4,090	--	--
1984	122	1,600	P	--
1985	284	2,290	152	2,140
1986	406	2,940	150	2,790
1987	612	3,760	327	3,430
1988	986	6,070	508	5,560
1989	1,040	5,930	532	5,400
1990	532	4,280	488	3,790
1991	762	5,000	737	4,260
1992	308	3,030	471	2,560
1993	605	3,610	394	3,220
1994	609	4,240	519	3,720
1995	216	2,605	606	2,000
1996	504	3,580	520	3,060
1997	721	5,370	554	4,820
1998	--	2,730	P	--

2000). Hill (1996) found no statistical link between ground-water withdrawals and streamflow during 1983–91 in the study area.

Land Use and Cover

Most of the area upstream of the Waimaluhia Reservoir is occupied by a botanical garden, two golf courses, and the Hawaii Loa campus of Hawaii Pacific University. The 420-acre Ho’omaluhia Botanical Garden (fig. 1) surrounding the reservoir is a public park operated by the City and County of Honolulu and was built at the same time as the reservoir. The park specializes in trees and shrubs from tropical locations worldwide with areas for camping and horseback riding. In addition to the 26-acre Waimaluhia Reservoir, a smaller 1.5 acre wildlife pond was built along Hooleinaiwa Stream (fig. 1). Upstream of the park and reservoir to the east and southeast is the 216-acre Pali Golf Course completed by 1957, the 220 acre Koolau (originally Minami) Golf Course built between 1989 and 1991, and the Hawaii Loa campus which occupies about 24 of 142 acres within the watershed. Residential areas upstream of the reservoir occupy about 50 acres with most of the housing located to the east. The H-3 Highway which crosses the basin roughly east to west occupies about 120 acres including easements. The remaining 879 acres is undeveloped conservation zoned land. Parts of both Likelike and Pali Highways cross the drainage basin near the Koolau Range (fig. 1).

Highway construction within the Waimaluhia Reservoir drainage basin began in 1983 (table 3) with the construction of the Halekou Interchange upstream of station 2656 (fig. 1). Numerous court injunctions delayed the construction at various times (table 3). Construction of the Windward Highway segment of the H-3 Highway, which affects most of the basin, began in the summer of 1989 and ended in the summer of 1992 (table 3). The highway segments upstream of the reservoir were constructed by cut and fill techniques. The Windward Highway from Likelike Highway to the Halekou interchange was briefly opened to traffic from March 1992 to August 1993. The entire H-3 Highway system was opened in December of 1997.

Soils in the study basin have been classified as mostly Lolekaa with some Kaneohe silty clays of the

Table 3. Chronology of construction activities at the Halekou Interchange and Windward Highway segments of the H-3 Highway, Kamooalii Stream drainage basin, Oahu, Hawaii, 1983–98

[Locations of construction activities and stream-gaging stations are shown in figure 1; start and end dates provided by the State of Hawaii, Department of Transportation]

Construction activity	Downstream gaging stations	Start date	End date
Halekou Interchange[1]	2656, 2722	02/22/83	12/01/83
		03/02/84	07/31/85
		11/04/85	02/28/86
		11/02/86	12/31/86
		06/15/87	09/30/88
Windward Highway segment	2656, 2709, 2722	06/19/89	06/92

[1] Work on Halekou Interchange interrupted by court injunctions

humic latosols great soil group (Foote and others, 1972). These soils are well drained, dark red to brown, and highly erodible on steep slopes (Foote and others, 1972).

Erosion-mitigation methods used during highway construction consisted of erosion-cloth barriers or silt fences used along stream channels, loose-rock check dams in channels upstream of station 2656, and hydromulching and fabric covering on cut-and-fill slopes. Erosion-mitigation methods used during the golf course construction were not determined for this study.

Most of the basin is covered with vegetation, either natural or cultivated. Natural vegetation is diverse, with hau trees growing along the stream channels and guava and Java plum trees, false staghorn fern, and various grasses predominating elsewhere (U.S. Army Corps of Engineers, 1974). A 16-acre forest of eucalyptus and aracaria trees is to the southeast of the reservoir and about 30 acres of banana cultivation continues in the park to the northwest of the reservoir (U.S. Army Corps of Engineers, 1974). Other cultivated areas include grasses on two golf courses. Downstream of the reservoir are additional banana plantations in the Luluku Stream basin both upstream (about 40 percent of the drainage area) and downstream of station 2709.

Previous Studies

A number of design memorandums covering the hydrology, geology, and design of the flood control reservoir and surrounding park and background of the study area were published by the U.S. Army Corps of Engineers (1972, 1973, 1974, 1975a, 1975b) along with a number of environmental impact statements (EIS) such as U.S. Army Corps of Engineers (1975c). Additional background information on the study area can be found in the many EIS for the H-3 Highway such as U.S. Department of Transportation, Federal Highway Administration (1980) as well as the Kamooalii Watershed Wells EIS (City and County of Honolulu, Board of Water Supply, 1984).

Jones and others (1971) conducted a sediment-transport reconnaissance study for Oahu and operated station 2705 from 1967 to 1969 immediately downstream of the dam and Luluku Stream inflow (fig. 1). A suspended-sediment yield of 910 tons/mi^2/year was estimated for the drainage basin of this station. Jones and others (1971) also computed specific weight (bulk density) for suspended sediment from five windward Oahu streams. These values ranged from 53 to 61 lb/ft^3 with an average of 57 lb/ft^3. With the completion of the flood-control project in 1981, an operations and maintenance manual was published (U.S. Army Corps of Engineers, Honolulu District, 1981). The reservoir was designed to hold 260 acre-ft of water but because an island within the reservoir was built larger than planned, the estimated volume at the time of completion (1980) was 235 acre-ft (Jim Pennaz, U.S. Army Corps of Engineers, written comm., 1990). The design sediment deposition rate of 2 acre-ft/yr was based on an annual sediment yield of 1,500 tons/mi^2/yr from the drainage area contributing to the reservoir, an average sediment bulk density of 65 lb/ft^3, and a reservoir trap efficiency of 60 percent (U.S. Army Corps of Engineers, Honolulu District, 1981). Trap efficiency is the percentage of sediment delivered to the reservoir that is trapped and deposited in the reservoir. The U.S. Army Corps of Engineers conducted a sediment survey in 1990 and determined the reservoir volume to be 218.1 acre-ft (Jim Pennaz, U.S. Army Corps of Engineers, written commun., 1990).

Wong and Hill (1992) presented bathymetric maps for Waimaluhia Reservoir for years 1983 and 1988 as well as a brief discussion of the data collection methodology. Hill (1996) discussed the construction effects of the H-3 Highway as of 1991 on the streamflow and suspended-sediment loads at stations 2656, 2709, and 2722. Hill (1996) concluded that low-flows increased at station 2709 and decreased at station 2722 during construction, and that suspended-sediment loads increased at station 2656, did not change at station 2722, and decreased at station 2709 as a result of highway construction.

METHOD OF BATHYMETRIC SURVEY

Sediment accumulation in Waimaluhia Reservoir was calculated by conducting bathymetric surveys using monumented cross sections. A total of 30 cross sections were established (fig. 2). The end points of each cross section were monumented with pipes set in concrete. Horizontal angles, vertical angles, distances between monuments and an arbitrary horizontal datum were measured by the State of Hawaii, Department of Transportation, Highway Division, in December 1983 and used to compute northings, eastings and altitudes for all monuments. All altitudes are relative to mean sea level.

Field data for each survey were processed using a geographical information system (GIS) program to plot all data points for manual drawing of bathymetric contours of the reservoir bottom. These contours were then digitized back into the GIS program which was used to compute the area and volume for each survey.

Cross-sectional surveys were made in September 1983, November 1988, August 1990, September 1991, September 1992, August 1993, July 1994, September 1995, and July 1998 (table 4). In 1983, all 30 original cross sections were surveyed, whereas in the other years between 20 to 26 cross sections were surveyed. Table 4 lists the cross sections surveyed in each year that were converted into digital form to be used in the GIS program. Cross sections A1 and A2 were used only for the 1995 and 1998 surveys and were created to avoid using the long COE-A-East and -West cross-sections (fig. 2).

Field Techniques

During each survey, a tagline made of buoyant non-stretching material was attached to the two monuments defining each cross section. Because of wave action and wind deflection, positional coordinates determined from the tagline are considered accurate to the nearest foot. The water surface altitude of the reservoir was monitored at a staff plate mounted on the outlet structure (fig. 2) to the nearest hundredths of a foot at the beginning, midpoint, and end of each day of the survey. The depths from the water surface to the bottom of the reservoir were determined to a precision of 0.01 ft with an accuracy of 0.05 ft because of wave action. Depths were measured with an electronic sounder in the 1983 survey. The 1990 and 1991 surveys used a different electronic sounder than the 1983 survey and the 1992 to 1998 surveys used a manual sounding weight. The manual sounding weight used in the 1990 to 1998 surveys was constructed with an 8-in. diameter perforated base designed to prevent sinking into soft sediments. The 1988 survey used a surveying rod with a precision of 0.1 ft and a manual sounding weight with a precision of 0.01 ft and an estimated accuracy of 0.1 ft. The surveying rod used in 1988, and in subsequent surveys where vegetation growth near the shoreline interfered with use of the sounder, was modified for use in soft sediment. The modification involved the addition of an 8-in. diameter perforated wood base designed to prevent the rod from sinking into soft sediments. Both the surveying rod and the manual sounding weight were constructed in a way that all readings were direct.

Bulk density, also called unit or specific weight, is the ratio of mass to the bulk (volume plus pore space) of a soil sample and is used to estimate the mass of a volume of soil too large to weigh, such as an acre-ft (Blake, 1965). Samples of one-liter volume were collected from the reservoir bottom using a clam-shell sampler at selected locations in August 1993 (fig. 2). A 2-in. diameter core sampler was used in October 2000 to collect samples of various volumes depending on core length. Bulk density was then computed by drying the sample at 105°C to a constant weight, weighing, and dividing the sample mass by sample volume (Blake, 1965).

Table 4. Cross sections surveyed by calender year in Waimaluhia Reservoir, Oahu, Hawaii, 1983–98
[X, cross section surveyed; -, not surveyed; unpublished data in files at U.S. Geological Survey, Hawaii District]

Cross section	Sept. 1983	Nov. 1988	Aug. 1990	Sept. 1991	Sept. 1992	Aug. 1993	July 1994	Sept. 1995	July 1998
A1	-	-	-	-	-	-	-	X	X
A2	-	-	-	-	-	-	-	X	X
B1	X	X	X	X	X	X	X	X	X
B2	X	X	X	X	X	X	X	X	X
B3	X	-	X	X	X	X	X	X	X
B4	X	X	X	X	X	X	X	X	X
COE-16	X	-	-	-	-	-	-	-	-
COE-19	X	-	-	-	-	-	-	-	-
COE-21	X	X	-	-	-	-	-	-	-
COE-A-EAST	X	X	X	X	X	X	X	-	-
COE-A-WEST	X	X	X	X	X	X	X	-	-
COE-C	X	X	X	X	X	X	X	X	X
COE-NOLL	X	-	-	-	-	-	-	-	-
COE-TED	X	X	X	X	X	X	X	X	X
K3	X	-	X	X	X	X	X	X	X
K4	X	X	X	X	X	X	X	X	X
K5	X	X	X	X	X	X	X	X	X
K6	X	-	X	X	X	X	X	X	X
QW1	X	X	X	X	X	X	X	X	X
QW2	X	X	X	X	X	X	X	X	X
QW3	X	-	X	X	X	X	X	X	X
QW4	X	X	X	X	X	X	X	X	X
R1	X	X	X	X	X	X	X	X	X
R2	X	X	X	X	X	X	X	X	X
R3	X	-	X	X	X	X	X	X	X
R4	X	-	X	X	X	X	X	X	X
R6	X	X	X	X	X	X	X	X	X
R7	X	X	X	X	X	X	X	X	X
R8	X	X	X	X	X	X	X	X	X
R9	X	X	X	X	X	-	-	-	-
R10	X	X	X	X	X	X	X	X	X
TED-NOLL	X	-	X	X	X	X	X	X	X
Total number surveyed	30	20	26	26	26	25	25	25	25

Data Processing

Northings, eastings, and altitudes (x, y, and z coordinates) for all points along the cross sections were computed with a computer program written in BASIC using the coordinates of the cross sectional monuments, the altitude of the water surface, measurements of distances between monuments, and measured depths. The design shoreline altitude of 160.0 ft was used for creating the bathymetric contour maps and as the datum in the reservoir volume calculations. The initial shoreline was digitized from a 1983 aerial photograph with a scale of 1:1,200. The data points were plotted on a map of the reservoir and the bathymetric contour lines were drawn manually at a 2 ft-contour interval for each survey. The 1983 bathymetric map was drawn using 1 ft-contour intervals with additional data from the Corps of Engineers. The contours were then digitized into the GIS program. Reservoir volumes were computed from the digitized contours by the GIS program using a triangulated irregular network (TIN) algorithm. A TIN consists of thousands of adjoining triangles with x, y, and z coordinates assigned to all vertices, creating a tri-dimensional surface model of the reservoir bottom. Volume is then computed by summing the individual volumes determined by multiplying the area of the triangular plane by its altitude. The number of digitized points used to define the contours determined the number of triangular planes used to determine the volume. The TIN and previous volume-calculation methods such as the stage-area curve (Heinemann and Dvorak, 1963), average contour area (Heinemann and Dvorak, 1963), prismoidal formula (Moffit and Bouchard, 1987), and modified prismoidal or conic method (Heinemann and Dvorak, 1963), were compared using the 1983 survey data. The areas between the 2 ft-contour intervals used in all these other computation methods were computed by the GIS program. The results are shown in table 5 ranked by computation accuracy, with the stage-area curve being the least accurate. Results of this comparison indicate that the TIN computed volume is slightly less than those computed by other methods in this particular case.

The 1983, 1988, and 1990 data were processed with the ARC/INFO GIS program version 5.0, the 1991 to 1993 data were processed using version 6.0 and the 1994 to 1998 used version 7.0. Computational differences in the TIN algorithms between versions were slight, the main modifications were between versions 5.0 and 6.0, with version 6.0 adding computations in double precision (Environmental Systems Research Institute, 1991).

Although quality control of bathymetric data consisted of surveying the same cross sections for each survey, this was not always possible because of vegetation growth near the shoreline and next to some cross section monuments. Some monuments were lost between surveys and were re-established as close as possible to the original location. Graphical plots of each cross section were compared with plots of the same cross section from previous surveys to verify that the correct start and end points of the monuments were used. To verify horizontal distances, the first 200 ft of tagline distance was rechecked in 1994 against a steel tape and found to be within 0.1 ft accuracy. Therefore, the location differences are considered insignificant and volume calculation differences are considered negligible. Accuracy of vertical measurements was confirmed by checking the first 10 ft of the sounder before each survey. Volumetric computations were corroborated by comparing a mean depth computed by dividing the volume by the area versus the mean depth computed from all the data points collected.

SEDIMENT ACCUMULATION

Rates of sediment accumulation in Waimaluhia Reservoir were determined by comparing the changes in reservoir volume between surveys. These volumes were computed from the bathymetric maps derived from the field data. Bulk-density data were used to determine the sediment yield of the basin and the trap efficiency of the reservoir.

Computed reservoir area and volume for each survey are shown in table 6. The total loss of volume during the study period (1983–98, 14.9 years) was 30.3 acre-ft which corresponds to an average loss rate of 2.0 acre-ft/yr. During the 1983–88 construction of the Halekou Interchange (table 3) the loss was 5.9 acre-ft for an average loss rate of 1.1 acre-ft/yr. In the 3.9 years between the November 1988 and September 1992 surveys, 19.0 acre-ft of sediment was deposited, which corresponds to an average sedimentation rate of 4.9 acre-ft/year. Construction of the Windward Highway segment spanned most of this period; the Koolau golf course was also built in this period. The total loss of reservoir volume from 1992 to 1998 after all intensive construction work was completed was 5.4 acre-ft which corresponds to a loss rate of 0.9 acre-ft/yr. For the entire period of intensive construction works during 1983–92 the total loss was 24.9 acre-ft for a loss rate of 2.7 acre-ft/yr.

Bathymetry

Figures 3, 4, 5, and 6 are the bathymetric maps for 1983, 1988, 1993, and 1998 surveys, respectively. These maps illustrate that the shape of the reservoir bottom changed most on the eastern side of the reservoir where Kamooalii Stream flows into the reservoir. Figure 7 shows that between 1983 and 1998, most of the deposition occurred where the streams flow into the reservoir and in the lower altitudes of the reservoir. Table 6 shows a reduction in reservoir surface-area with time.

Each survey indicated loss of reservoir volume except for 1993, which indicated gain (table 6). Field data from this survey showed that some cross sections were deeper in 1993 than in 1992. This was mostly in

Table 5. Results of selected volumetric computation methods, Waimaluhia Reservoir, Oahu, Hawaii, 1983 survey data

Method	Volume (acre-feet)
Stage-area curve	242.8
Average contour area	242.7
Prismoidal	242.7
Modified prismoidal or conic	241.5
Triangular irregular network	239.6

Table 6. Computed area, volume, average bottom altitude, and change in volume of Waimaluhia Reservoir, Oahu, Hawaii, 1983–98

[Area, volume, and calculated bottom-altitude values are relative to 160.0 feet mean sea level reservoir pool altitude; bottom altitude calculated by dividing volume by area, and subtracting that value from 160.0 feet; change in volume calculated by subtracting volume for previous survey's volume; --, not applicable]

Date of survey	Number of measure-ments	Mean bottom altitude (feet)	Maximum depth (feet)	Surface area (acre)	Volume (acre-feet)	Calculated bottom altitude (feet)	Change in volume (acre-feet)	Time between surveys (years)
September 1983	1,418	151.5	17.8	26.8	239.6	151.1	--	--
November 1988	1,585	151.9	16.2	26.7	233.7	151.3	-5.9	5.2
August 1990	1,709	152.1	15.9	26.5	223.1	151.6	-10.6	1.8
September 1991	1,674	152.2	15.9	26.3	218.6	151.7	-4.5	1.1
September 1992	1,638	152.0	15.9	26.3	214.7	151.8	-3.9	1.0
August 1993	1,464	152.1	15.7	26.4	215.8	151.8	+1.1	0.9
July 1994	1,630	152.3	15.4	26.3	213.9	151.9	-1.9	0.9
September 1995	1,596	152.2	15.7	26.4	212.3	152.0	-1.6	1.2
July 1998	1,584	152.2	15.7	26.2	209.3	152.0	-3.0	2.8

the eastern and southern parts by cross sections B1, B2, COE-A East and West, COE-C, COE-TED, QW 1, QW4, R7, and R8 (fig. 2). Other cross-section depths were equal or shallower than in 1992. A possible explanation for this volume increase could be the settlement or compaction of sediments following the high rates of deposition during 1990–92. Bulk-density data (table 7) and visual observation indicate that most of the sediment deposited by 1993 was fine sediment consisting of silts and clays less than 0.062 mm in size. Such material can be subject to compaction.

Sediment Yield and Trap Efficiency

The sediment yield of the surrounding drainage basin and trap efficiency of Waimaluhia Reservoir were determined from the bulk-density and suspended-sediment data. Bulk-density data determined from bottom samples are shown in table 7. All samples in 1993 were, except for a few leaves and shells from freshwater clams, close to 100 percent finer than 0.062 mm by visual examination. The average density of the 6 samples collected in 1993 was 25 lb/ft^3 (0.40 g/cm^3). Core samples at deeper penetration depths (table 7) were collected in 2000. These samples were visually also close to 100 percent finer than 0.062 mm in particle size. Samples taken at cross sections B4, COE-C, and COE-TED contained some sand and gravel only in the top 2 to 3 inches of the reservoir bottom. The average density of the 6 samples collected in 2000 (table 7) was 29 lb/ft^3 (0.46 g/cm^3), not much different from the 1993 bulk densities. This density is low compared to the average densities of 40 to 65 lb/ft^3 for submerged clay-silt mixture sediments (Geiger, 1963; Lara and Pemberton,

Figure 3. Bathymetric map of Waimaluhia Reservoir, 1983, Oahu, Hawaii (from Wong and Hill, 1992).

Figure 4. Bathymetric map of Waimaluhia Reservoir, 1988, Oahu, Hawaii (from Wong and Hill, 1992).

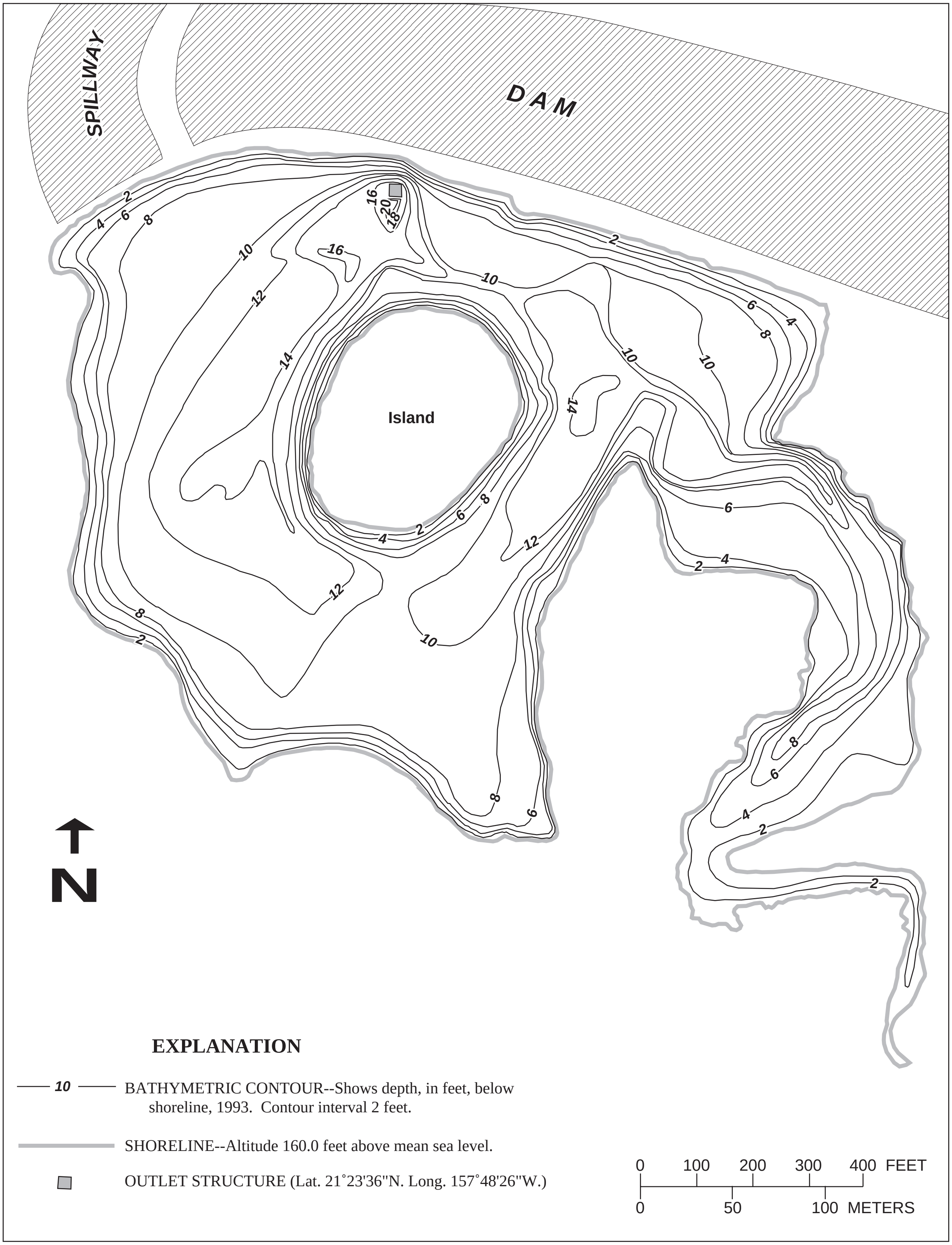

Figure 5. Bathymetric map of Waimaluhia Reservoir, 1993, Oahu, Hawaii.

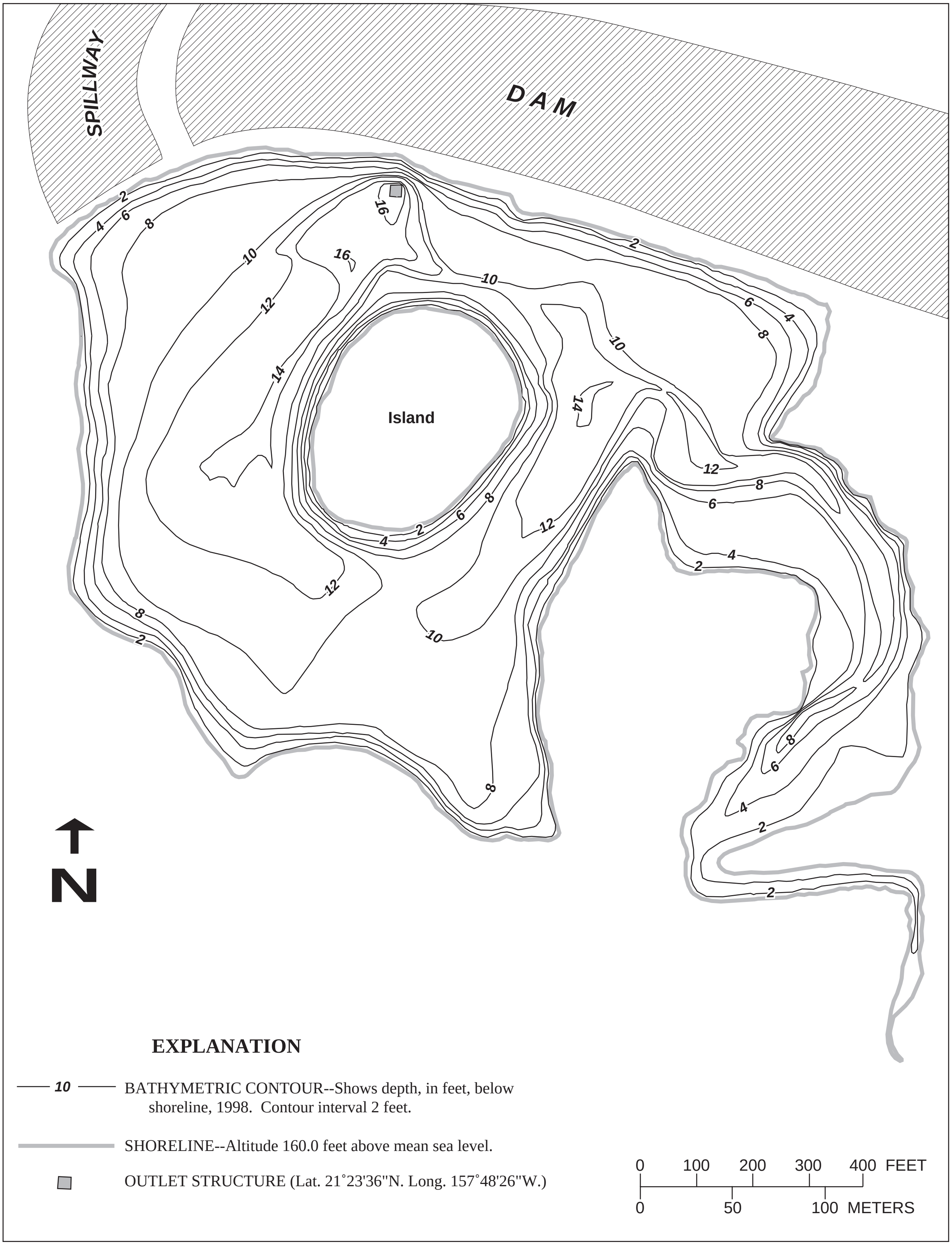

Figure 6. Bathymetric map of Waimaluhia Reservoir, 1998, Oahu, Hawaii.

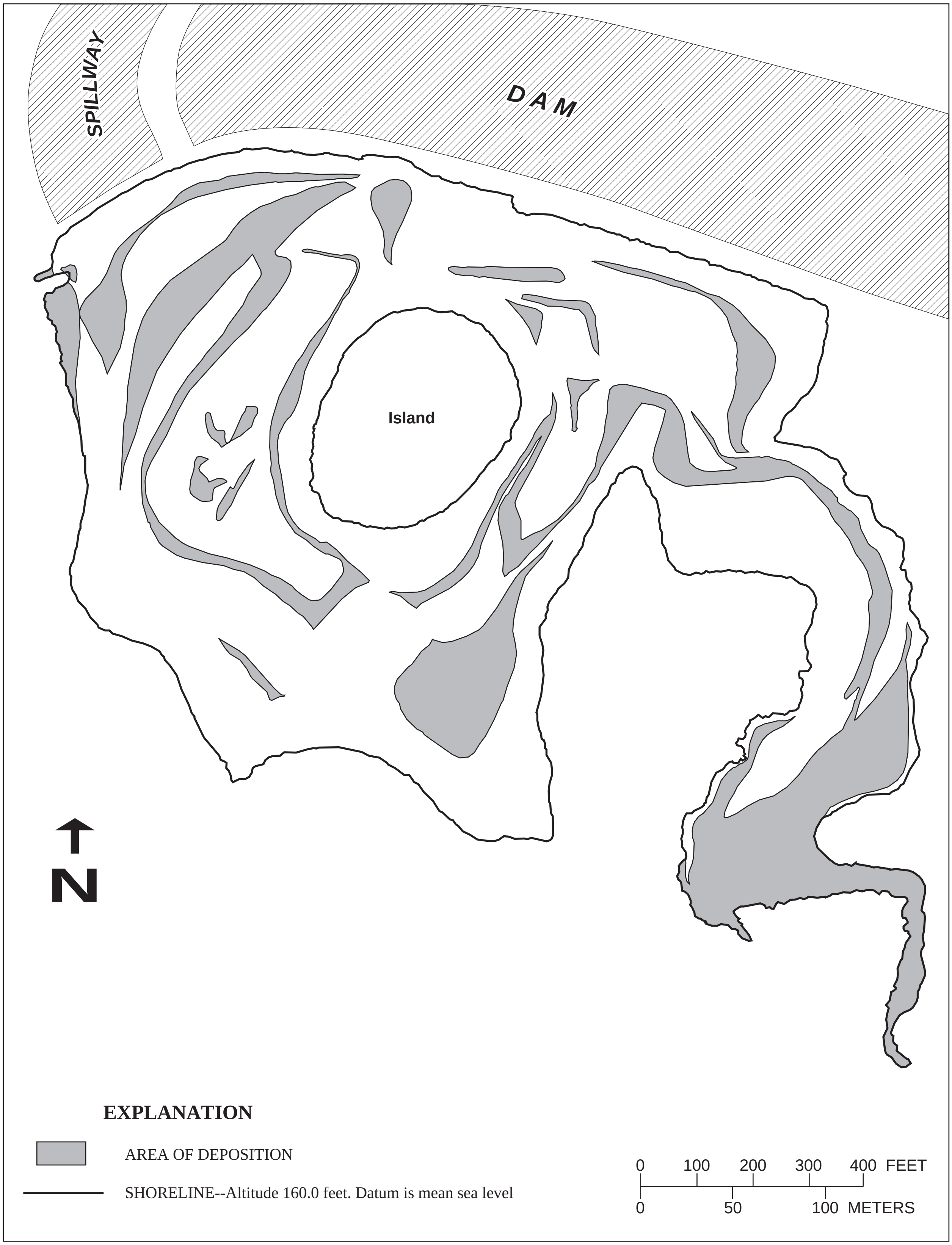

Figure 7. Areas of sediment deposition from 1983 to 1998 in Waimaluhia Reservoir, Oahu, Hawaii.

Table 7. Bulk density of bottom material from Waimaluhia Reservoir, Oahu, Hawaii, August 1993 and October 2000

[cm^3, cubic centimeter; g/cm^3, grams per cubic centimeter]

Cross section	Station (feet)	Depth to bottom (feet)	Change in depth since 1983 (feet)	Penetration depth of sample (feet)	Mass (gram)	Volume (cm^3)	Bulk density (g/cm^3)
			August 1993				
B3	205	9.19	-0.58	0.3	400	1,000	0.40
B4	245	7.16	-1.15	0.3	368	1,000	0.37
COE-C	130	8.12	-0.49	0.3	452	1,000	0.45
COE-TED	130	1.72	-4.83	0.3	168	440	0.38
QW1	120	9.57	-0.70	0.3	392	1,000	0.39
QW2	140	12.02	-0.68	0.3	391	1,000	0.39
			October 2000				
B4	265	6.95	-1.53	1.61	366	890	0.41
COE-C	140	8.04	-0.72	1.18	264	650	0.41
COE-TED	125	2.17	-4.71	1.14	489	630	0.78
K6	115	11.35	-6.51	1.17	285	650	0.44
QW1	125	10.18	-0.36	1.41	262	780	0.34
QW2	140	11.56	-1.35	1.35	272	740	0.37

Table 8. Annual suspended-sediment loads at stream-gaging stations in the Kamooalii drainage basin, Oahu, Hawaii, water years 1981–98

[Values in tons; --, no data; P, partial year, more than one month of no data; complete station numbers are preceded by 16 and end in 00; e, estimated; estimated values of suspended-sediment loads were estimated using the partial years of record at station 2709 and by comparison of monthly suspended-sediment load data for the concurrent periods of record at stations 2709 and 2722]

Water Year	Station 2656 Right Branch Kamooalii Stream	Station 2722 Kamooalii Stream	Station 2709 Luluku Stream	Pass-through load Kamooalli Stream less Luluku Stream
1981	--	723	--	--
1982	--	3,210	--	--
1983	P	173	--	--
1984	23.7	76.6	P	e45.5
1985	541	336	43.0	293
1986	472	322	91.1	231
1987	631	1,190	402	788
1988	1,730	2,240	485	1,755
1989	1,220	1,290	180	1,110
1990	1,160	593	52.6	540
1991	512	1,270	333	937
1992	64.8	148	70.4	77.6
1993	421	801	185	616
1994	278	606	193	413
1995	63.7	222	66.1	156
1996	1,940	1,370	884	486
1997	146	424	135	289
1998	--	131	P	e116

1963) and suspended-sediments (57 lb/ft^3) sampled by Jones and others (1971). However, the 29 lb/ft^3 value falls within the range of densities, 20 to 120 lb/ft^3, sampled throughout the United States for permanent pool reservoirs (Lara and Pemberton, 1963).

Multiplying the total volume of sediment deposited in the reservoir, 30.3 acre-ft, by the average bulk density, 29 lb/ft^3 gives a total of 19,100 tons for the net mass of sediment trapped in the reservoir from 1983 to 1998. This mass includes bedload (the part of sediment usually made up of gravel, cobbles, and boulders, that moves along the streambed by rolling or sliding), and suspended-sediment load. For the period of 1985 to 1997, where complete years of data are available, the suspended-sediment load that passed through the reservoir was 7,690 tons. This load was computed by subtracting the suspended-sediment load at station 2709 from the suspended-sediment load at station 2722 (table 8). Bedload at both stations was ignored because all bedload into the reservoir is trapped. For the period of the sediment surveys, 1983 to 1998, the suspended-sediment load at station 2709 for water years 1984 and 1998 was estimated. Loads for these years were estimated by using the partial years of record from water years 1984 and 1998 at station 2709 and by comparison of monthly suspended-sediment load data for the period of concurrent record from both stations 2709 and 2722. Estimates of suspended-sediment load for these two water years increases the suspended-sediment load that passed through the reservoir to 7,850 tons (table 8). The total amount of sediment delivered to the reservoir is the sum of the 19,100 tons deposited and the 7,850 tons discharged, or 26,950 tons. This number divided by the reservoir's drainage area of 3.20 mi^2 and the time of 14.9 years gives a mean annual sediment yield of 565 tons/mi^2/yr. This number is about 38 percent of the 1,500 tons/mi^2/yr used in the reservoir design.

The trapping efficiency of the reservoir was computed by the following equation:

$$E_t = (Lt/(L_t + L_p)) \times 100 \text{ percent}, \qquad (1)$$

where E_t = trap efficiency,

L_t = total sediment load trapped in reservoir = 19,100 tons, and

L_p = suspended sediment load passed through reservoir = 7,850 tons.

A trapping efficiency of 71 percent was computed using equation 1. This value compares closely with an estimate of trap efficiency using the capacity/inflow relationship described by Brune (1953). Inflow to the reservoir was computed using the simple water-budget relation that outflow equals inflow. Because groundwater seepage was negligible and the seepage that was observed flowed into the stream upstream of station 2722, and because rainfall on the reservoir (75 in/yr) exceeded the evaporation from the reservoir (less than 50 in/yr), the flow measured at station 2722 minus the flow at station 2709 equals the outflow. From table 2, the average outflow from water years 1995 to 1997 was 3,600 ft^3/s-days/yr or 7,140 acre-ft/yr. The capacity of the reservoir was 209.3 acre-ft in 1998, using this value, the capacity/inflow is 0.03. From figure 6 in Brune (1953) the trap efficiency is 70 percent with a possible range of 60 to 80 percent. Both the value from the Brune (1953) method and the value calculated in equation 1 are higher than the 60 percent design value.

SUMMARY

A major highway constructed upstream of Waimaluhia Reservoir, in a high-rainfall area on the island of Oahu, began in 1983 and ended in 1998. The U.S. Geological Survey in cooperation with the Hawaii State Department of Transportation and the Federal Highway Administration conducted periodic bathymetric surveys to measure sediment accumulation in the reservoir during this period. The objective of these surveys was to determine if the decrease in the reservoir storage-capacity resulted from sediment deposition during highway construction and if the loss rate exceeded the design storage-capacity loss rate of 2.0 acre-feet per year. Most of the land disturbances associated with the highway construction occurred from 1983 to 1992 and were particularly intense between 1989 and 1992, coinciding with the construction of a golf course upstream of the reservoir.

The monuments used for the bathymetric surveys were established in 1983. Bathymetric surveys were conducted in 1983, 1988, annually from 1990 to 1995, and in 1998. The bulk densities of several samples of sediments deposited in the reservoir were measured in 1993 and 2000. Suspended-sediment loads were measured since 1983 at one station upstream of the reservoir and at another station downstream of the reservoir. The rate of sediment accumulation for the study period (from 1983 to 1998) was 2.0 acre-feet per year equaling the design loss rate. During the period of intense construction activities (1983–92), the loss rate was 2.7 acre-feet per year. The highest loss rate of 4.9 acre-feet per year was during the period of greatest land disturbances from 1988 to 1992.

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