STREAMFLOW AND SUSPENDED-SEDIMENT LOADS BEFORE AND DURING HIGHWAY CONSTRUCTION, NORTH HALAWA, HAIKU, AND KAMOOALII DRAINAGE BASINS, OAHU, HAWAII, 1983–91

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Streamflow and Suspended-Sediment Loads Before and During Highway Construction, North Halawa, Haiku, and Kamooalii Drainage Basins, Oahu, Hawaii, 1983–91

By Barry R. Hill

Abstract

Concern over potential effects from construction of the H-3 highway on Oahu, Hawaii, prompted a long-term study of streamflow and suspended-sediment transport at a network of five stream-gaging stations along the highway route. This report presents results for 1983–91, which included preconstruction and construction periods at all stream-gaging stations.

Annual rainfall, streamflow, and suspended-sediment loads were generally higher during construction than before construction. Data collected before and during construction were compared using analysis of covariance to determine whether streamflow and suspended-sediment loads changed significantly during construction after accounting for effects of increased rainfall.

Streamflow at stream-gaging stations was compared with streamflow at an index stream-gaging station unaffected by construction. Streamflow data were divided into low- and high-flow classes, and the two flow classes were analyzed separately. Low flows increased 117 percent during construction at one station. This increase probably was related to the removal of vegetation for highway construction. Low flows decreased 28 percent at another station, probably as a result of increased ground-water withdrawals and highway construction activities. No significant changes in low flows were detected at the other stations, and no significant changes in high flows were detected at any stations.

Suspended-sediment loads increased significantly during construction at three stations. Highway construction contributed between 56 and 76 percent of the suspended-sediment loads measured at these stations during construction. Loads did not change significantly at a station downstream of a reservoir, and loads decreased at a station downstream of a drainage basin that was heavily used for agriculture before construction.

Suspended-sediment concentrations were used to assess compliance with applicable State water-quality standards. State water-quality standards for suspended sediment frequently were exceeded during construction. Standards occasionally were exceeded before construction.

INTRODUCTION

The H-3 highway, currently (1994) under construction, will be a major highway across the Koolau Range on the island of Oahu, Hawaii (fig. 1). Construction began after a lengthy environmental evaluation (U.S. Department of Transportation and State of Hawaii Department of Transportation, 1987). Potential effects of construction on streams along the route were an issue of public concern. In 1983, the U.S. Geological Survey, in cooperation with the State of Hawaii Department of Transportation, began a study of streamflow and suspended-sediment transport in these streams. The purpose of the study is to compare data collected before, during, and after highway construction to determine whether construction activities have affected streamflow and suspended-sediment transport. The purpose of this report is to identify and quantify effects of H-3 construction on streamflow and suspended-sediment loads

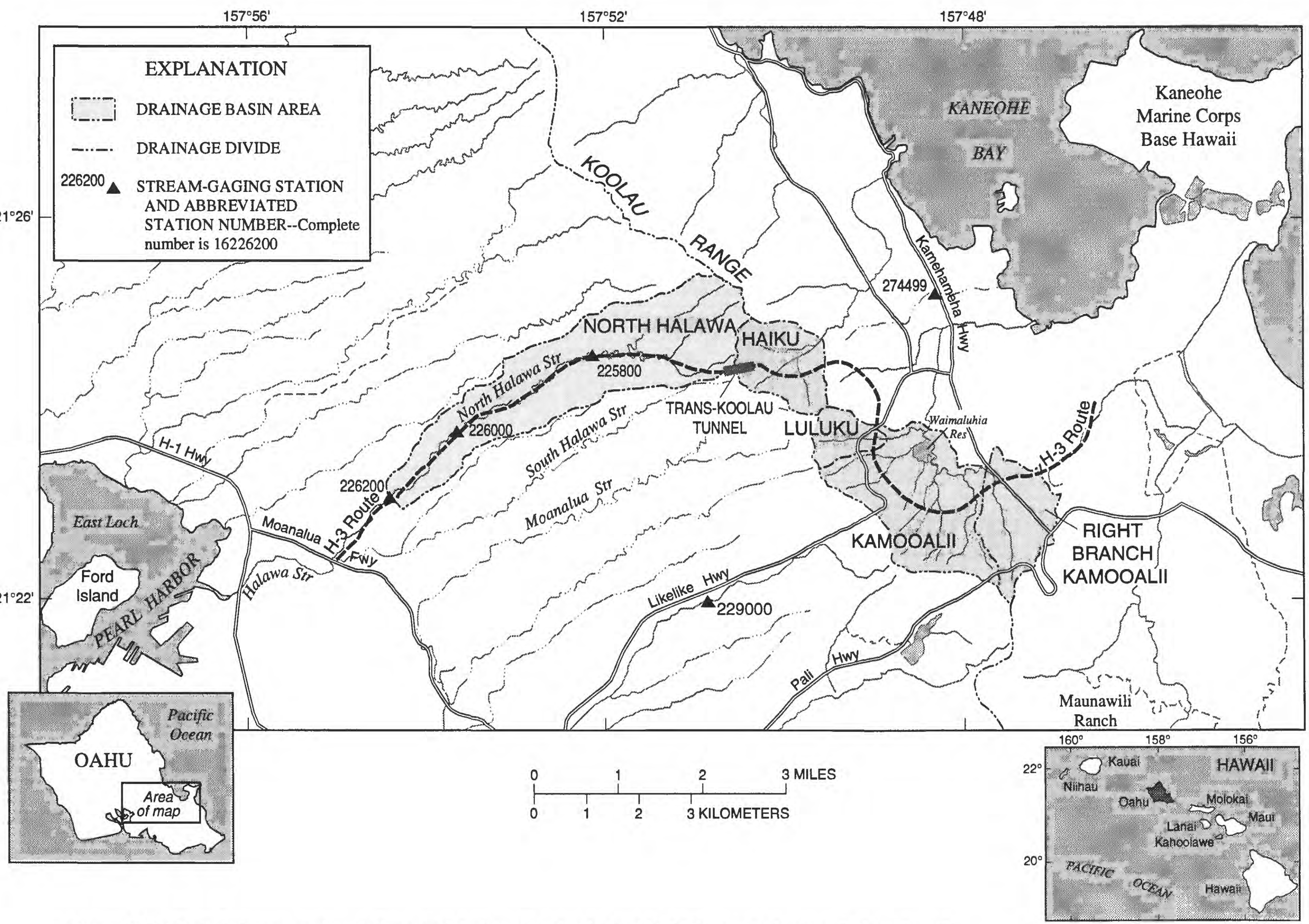

Figure 1. Selected stream-gaging stations and drainage basins in the H-3 highway study area, Oahu, Hawaii.

between 1983 and 1991, which included periods before and during construction. Additional data collected before 1983 were used at one station.

Rainfall, streamflow, and suspended-sediment data collected at a network of stream-gaging stations and miscellaneous sites (fig. 2) were used to determine whether streamflow and suspended-sediment loads changed significantly during construction. Changes due to construction were quantified by comparing data collected during construction to data collected before construction. Suspended-sediment concentrations were used to assess compliance with applicable State water-quality standards related to sediment transport. Daily, monthly, and annual values of streamflow, suspended-sediment concentration and discharge, and suspended-sediment size analyses have been published in the annual water-resources data reports of the U.S. Geological Survey (U.S. Geological Survey, 1982; Chinn and others, 1983, 1984, 1985, 1986, 1988; Nakahara and others, 1988; Nakahara and others, 1989; Matsuoka and others, 1991, 1992).

H-3 Highway Construction

The H-3 highway route traverses four drainage basins: North Halawa, Haiku, Kapunahala, and Kamooalii, which includes the Luluku drainage basin (figs. 1 and 2). The H-3 extends from the H-1 highway near the East Loch of Pearl Harbor on the leeward (southwestern) side of the Koolau Range to the Halekou interchange on the windward (northeastern) side, where the H-3 connects to a previously constructed section leading from Kamehameha Highway to Kaneohe Marine Corps Base Hawaii. The completed highway will consist of a cut-and-fill section in the lower North Halawa Valley, a viaduct through the upper North Halawa Valley, twin tunnels below the crest of the Koolau Range, a viaduct through the Haiku drainage basin, and a cut-and-fill section through the Kapunahala and Kamooalii drainage basins (U.S. Department of Transportation, Federal Highways Administration and State of Hawaii Department of Transportation, 1987). When completed, the total area affected by highway construction will constitute from 3 to 11 percent of the drainage basin areas upstream of the stream-gaging stations discussed in this report.

Construction of the H-3 highway has proceeded by sections (table 1). Construction has at times been halted by court actions, and the route has been modified to avoid sites of cultural importance. Access roads were built in the North Halawa and Haiku Valleys before construction of the highway. An exploratory tunnel was excavated below the crest of the Koolau Range before the larger traffic tunnels were excavated.

Erosion-control measures have been used throughout construction of the H-3 highway to reduce sediment delivery from construction areas in all affected drainage basins. These measures include erosion-cloth barriers installed on hillslopes and along channels, loose-rock check dams in channels, and hydromulching and installation of plastic netting on cut-and-fill slopes. Streamflow in several channel reaches in upper North Halawa Valley was diverted into culverts and buried during construction to prevent sediment disturbed by construction from reaching the stream.

Study Drainage Basins

The Koolau Range is the eroded remnant of the larger and younger of the two major shield volcanoes that formed the island of Oahu (Visher and Mink, 1964). Much of the windward side of the original Koolau Volcano has been eroded, leaving a steep windward slope indented with amphitheater-shaped valleys (Hinds, 1925), and a gentle leeward slope deeply dissected by roughly linear valleys.

Lithology of the study area consists primarily of basalt that was extruded in numerous gently dipping thin (less than 10 ft) flows of aa and pahoehoe lava (Visher and Mink, 1964). These flows are intruded by near-vertical dikes in the rift zone near the crest of the present Koolau Range (Visher and Mink, 1964). More recent volcanic rocks are exposed in small areas on the windward side of the study area (Takasaki and others, 1969). The gently sloping lower parts of the windward drainage basins and the valley floor of the North Halawa drainage basin are underlain by alluvium derived from erosion of the Koolau Range (Takasaki and others, 1969; Izuka, 1992).

The climate of Oahu is warm and humid. Average annual temperature ranges from 74° to 76°F in the study area; temperatures above 95°F and below 50°F are rare (U.S. Department of Commerce, 1961). The distribution of rainfall is affected by the prevailing northeasterly trade winds and the topography of the island. Orographic lifting and cooling of marine air

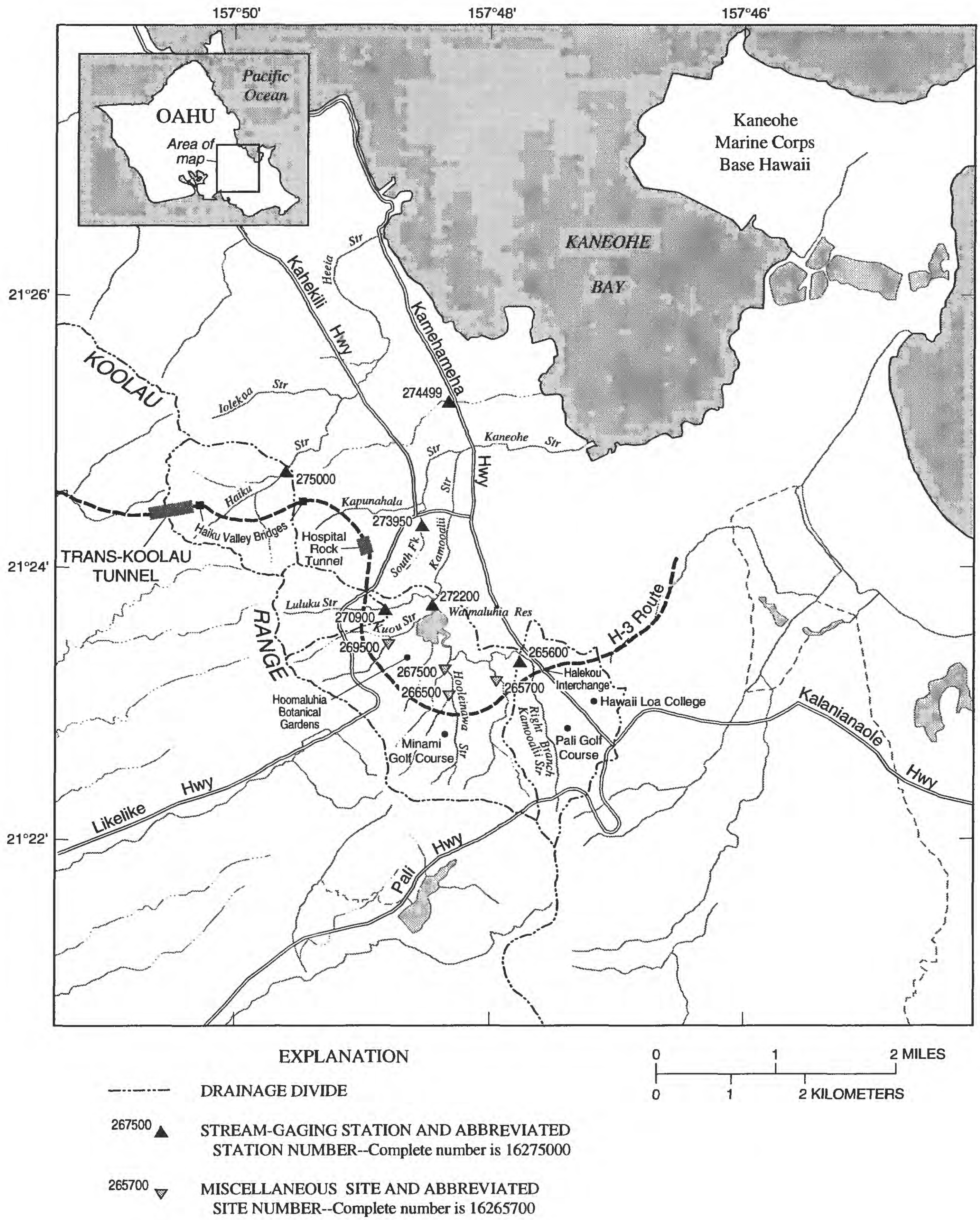

Figure 2. Selected stream-gaging stations and miscellaneous sites in the windward area of the H-3 highway study area, Oahu, Hawaii.

Table 1. Chronology of construction activities, H-3 highway construction project, 1983–92, Oahu, Hawaii

[Locations of construction activities and stream-gaging stations are shown in figures 1–3; station numbers are abbreviated, complete numbers are preceded by 16; do., ditto; --, construction activity in progress as of September 30, 1991. Start and end dates provided by the State of Hawaii, Department of Transportation, written commun., 1993]

Construction activity	Start date	End date
N. Halawa drainage basin—downstream stream-gaging station 226200		
N. Halawa access road	11/02/87	03/89
Exploratory tunnel	02/27/89	03/90
Drilled shaft test program	11/13/90	02/91
Trans-Koolau tunnel	03/19/91	--
N. Halawa viaduct	02/21/92	--
Haiku drainage basin—downstream stream-gaging station 275000		
Haiku access road	10/24/88	06/90
Exploratory tunnel	02/27/89	03/90
Haiku Valley bridges	08/07/89	03/91
Windward viaduct	01/08/90	--
Trans-Koolau tunnel	10/01/90	--
Kamooalii drainage basin—downstream stream-gaging stations 265600, 270900, and 272200		
H-3 highway	06/19/89	06/92
Right Branch Kamooalii drainage basin—downstream stream-gaging stations 265600 and 272200		
Halekou interchange[1]	02/22/83	12/01/83
do.	03/02/84	07/31/85
do.	11/04/85	02/28/86
do.	11/02/86	12/31/86
do.	06/15/87	09/30/88
Luluku drainage basin—downstream stream-gaging stations 270900 and 272200		
Hospital Rock tunnel	03/06/89	05/92

[1] Work on Halekou interchange interrupted by court injunctions

masses moving with the trade winds result in heavier and more frequent rainfall on the windward side and near the crest of the Koolau Range. The heaviest rainfall occurs about 0.5 to 1 mi leeward of the crest (C.K. Wentworth, written commun., 1942; Mink, 1960). Rainfall varies seasonally, with most rainfall falling between November and April. Average annual precipitation ranges from 75 to 150 in. on the windward side of the study area, and from 40 to more than 150 in. on the leeward side (U.S. Department of Commerce, 1961).

Streamflow in the study area is determined by geology and climate. Large quantities of rainfall and the presence of numerous low-permeability dikes result in storage of high-level ground water that maintains the base flow of streams on the windward side (Takasaki and others, 1969). As a result of the highly permeable bedrock and the orientation of dikes, ground water can flow between windward drainage basins. Rainfall infiltrating in one valley may emerge as streamflow in another (Hirashima, 1963; Takasaki and others, 1969). On the leeward side of the Koolau Range, dikes are uncommon (C.K. Wentworth, written commun., 1942). Infiltrating rainfall in the North Halawa Valley percolates to the basal aquifer and does not maintain base flows (C.K. Wentworth, written commun., 1942; Izuka, 1992). Streamflow in North Halawa Stream is intermittent and is dependent on runoff during rainfall, although discharge of small quantities of ground water from alluvial aquifers extends recession flows (Izuka, 1992).

The relative importance of the geomorphic processes responsible for the dramatic topography of the study area has been debated for many years. The role of chemical weathering in the warm, humid climate of Oahu has been stressed (Wentworth, 1928; Scott and Street, 1976). Stream piracy (Wentworth, 1928; Stearns and Vaksvik, 1935), rapid weathering at the water table (Wentworth, 1928), and plunge-pool erosion and ground-water sapping (Stearns and Vaksvik, 1935) have been suggested as causes of the unique amphitheater-shaped valleys of the Koolau Range. The most obvious process of physical erosion is mass wasting of shallow soil and saprolite on steep hillslopes in areas of high rainfall (Stearns and Vaksvik, 1935; Wentworth, 1943; White, 1949; Scott and Street, 1976; Wilson and others, 1992).

Soils of the study area have been classified as low humic latosols, humic ferruginous latosols, humic latosols, and hydrol humic latosols (Cline, 1955). The distribution of soils is related to rainfall; low humic latosols and humic ferruginous latosols are found on drier leeward stations, hydrol humic latosols are found in areas of high rainfall, and humic latosols occupy intermediate stations (Tamura and others, 1953; Sherman and Ikawa, 1967). Soils on the windward side primarily are humic latosols (Foote and others, 1972). Most of the mountainous areas of the study drainage basins were classified as "rough mountainous land" or "rock outcrop" (Foote and others, 1972), and little information is available on the soils of these areas.

Most of the native vegetation on the windward side of the study area has been replaced by cultivated crops, other non-native plants, and residential and commercial developments. Vegetation in the North Halawa Valley is representative of undisturbed forest in the leeward Koolau Range and includes native and introduced species.

North Halawa.--The North Halawa drainage basin is on the leeward side of the crest of the Koolau Range. North Halawa Stream flows into the East Loch of Pearl Harbor after joining South Halawa Stream downstream of stream-gaging station 226200 (figs. 1 and 2; numbers of stream-gaging stations used in this report are abbreviated by omitting the first two digits, 16, from the full station numbers). The drainage area upstream of station 226200, at an altitude of 160 ft, is 4.01 mi^2. Overall stream gradient is 0.074 ft/ft. The lower valley is deeply incised, with only a few small ephemeral tributaries. The channel in the lower valley is cut about 3 to 6 ft into the alluvium that forms the valley floor. The steep upper part of the drainage basin is less deeply incised, and has a dendritic drainage pattern with several intermittent tributaries. In the upper drainage basin, channels are cut into bedrock and include several waterfalls. The stream is more than 100 ft above the basal water table throughout the valley (C.K. Wentworth, written commun., 1942; Izuka, 1992), and flow in the main channel is intermittent in most years.

When completed, the H-3 highway will constitute about 4 percent of the drainage area upstream of station 226200. Before highway construction began in November, 1987, this drainage basin was undeveloped with the exception of the Halawa Shaft, built by the Honolulu Board of Water Supply in 1940 to collect ground water from the basal aquifer. There are no streamflow diversions in the drainage basin except temporary channel diversions related to highway construction; these diversions do not transfer surface water out of the drainage basin.

Rainfall, streamflow, and suspended-sediment data collection at station 226200 began in February, 1983. Rainfall and streamflow data have been continuously collected at station 226000 (fig. 1) since 1953. Data collection at station 225800 (fig. 1) began in April, 1991.

Haiku.--The Haiku drainage basin is on the windward side of the Koolau Range and adjoins the North Halawa drainage basin along the crest of the range (fig. 2). Drainage area upstream of stream-gaging station 275000, at an altitude of 272 ft, is 0.97 mi^2. Overall stream gradient is 0.267 ft/ft. The headwaters of Haiku Stream consist of steep cliffs where water flows over exposed bedrock and saprolite. An alluviated valley floor occupies the lower parts of the drainage basin, where the channel is composed mostly of boulders and cobbles. At station 275000, Haiku Stream flows perennially. Haiku Stream joins Iolekaa Stream downstream of station 275000 to form Heeia Stream, which flows into Kaneohe Bay (fig. 2).

Almost all of the drainage basin upstream of station 275000 is used for a U.S. Coast Guard navigational facility. A municipal well and water tunnel are located upstream of station 275000. The tunnel was constructed in 1940; the well was brought into service during the H-3 highway construction period in 1989. Highway construction in the Haiku drainage basin began in October of 1988 (table 1). The H-3 within Haiku drainage basin is constructed entirely as a viaduct, and covers about 3 percent of the drainage area for station 275000.

Streamflow data were collected before this study at station 275000 from 1914 through 1919 and from 1939 through 1977. Streamflow data collection for the H-3 study began in October, 1982, and suspended-sediment data were collected from December, 1983 through September, 1984 and from July, 1987 through the present (1994).

The South Fork Kapunahala drainage basin lies adjacent to the Haiku drainage basin on its southeast boundary. The drainage basin above station 273950, at an altitude of 120 ft, has an area of 0.40 mi^2 (fig. 2). The drainage basin consists of residential and agricultural lands. H-3 highway construction began in June, 1989 (table 1). Although streamflow data have been collected since 1987, suspended-sediment data are available only for 1991.

Kamooalii.--The Kamooalii drainage basin upstream of stream-gaging station 272200, at an altitude of 115 ft, is 3.81 mi^2 (fig. 2). This area includes the 1.11 mi^2 Right Branch Kamooalii drainage basin upstream of stream-gaging station 265600 and the 0.44 mi^2 Luluku drainage basin upstream of stream-gaging station 270900. Streamflow is perennial at all three stations. Kamooalii Stream joins Kapunahala Stream downstream of station 272200 to form Kaneohe Stream, which flows into Kaneohe Bay. Waimaluhia Reservoir, a flood-control reservoir, was constructed in 1980 upstream of the confluence of Luluku and Kamooalii Streams. Streamflow at station 272200 includes water flowing through Waimaluhia Reservoir and water from Luluku Stream that does not pass through the reservoir. Overall stream gradient at station 272200 is 0.095 ft/ft. The channels within the drainage basin are cut between 2 and 20 ft into alluvium, and are composed mainly of cobbles and gravel intermixed with finer sediment.

The Hoomaluhia Botanical Garden surrounding Waimaluhia Reservoir is a public park operated by the City and County of Honolulu (fig. 2). Below the park, most of the drainage basin has been developed for residential use. Above the park, most of the drainage basin consists of banana plantations or undeveloped land. The Likelike highway crosses the drainage basin above the H-3 highway. The Minami golf course was constructed above the park in 1989–91.

Several municipal wells and water tunnels are located in the Kamooalii drainage basin, including two wells that were brought into operation during the H-3 highway construction period. Two private wells for golf course irrigation also were drilled above station 265600 during the construction period. Water is sometimes pumped from Luluku Stream above station 270900 to irrigate banana plantations.

Highway construction in the drainage basin began in 1983 (table 1). The H-3 highway constitutes about 4 percent of the drainage area for station 272200. The area affected by the H-3 includes about 11 percent of the drainage area for station 270900 and 5 percent of the drainage area for station 265600.

Streamflow and suspended-sediment data collection at station 272200 began in 1976. Data from October, 1980 (after dam closure) through September, 1991 are used in this report. Streamflow and suspended-sediment data collection began in February, 1983 at station 265600 and in April, 1984, at station 270900. Streamflow data previously were collected at station 270900 from 1960–63 (low flow only), 1965–71, and 1971–84 (annual maximum only).

Suspended-Sediment Yields in the Koolau Range

Sediment data are sparse for the islands of Hawaii, but some previously collected sediment data are available for streams in and near the H-3 highway study area. These data can be usefully compared with data collected for the H-3 study by converting annual suspended-sediment loads to annual suspended-sediment yields. Annual suspended-sediment loads are quantities of suspended sediment, in mass units, transported during a year. Suspended-sediment loads usually are reported in tons. Annual suspended-sediment yields are suspended-sediment loads per unit of drainage area, and usually are expressed in tons per square mile, or tons per square mile per year. Sediment data for drainage basins with drainage areas similar to those of H-3 study drainage basins were collected for a 3-year period at eight stream-gaging stations in the central Koolau Range and in nearby areas (Jones and others, 1971), for 5 years at five stations in the same general area (Doty and others, 1981), and for 5 years at two stations in the Moanalua Valley (Shade, 1984). These data give some indication of the range of annual suspended-sediment yields for drainage basins both in undisturbed conditions and under mixed land use consisting of urban, agricultural, and conservation uses. Suspended-sediment yields for undisturbed drainage basins on the leeward side of the Koolau Range ranged from 24 to 1,770 $(t/mi^2)/yr$ (Jones and others, 1971; Doty and others, 1981; Shade, 1984). The single leeward drainage basin under mixed land use had a suspended-sediment yield of 970 $(t/mi^2)/yr$ (Jones and others, 1971). Undisturbed windward drainage basins had suspended-sediment yields ranging from 710 to 1,400 $(t/mi^2)/yr$, and mixed-use windward drainage basins had suspended-sediment yields ranging from 8.6 to 960 (t/mi^2)/yr (Jones and others, 1971; Doty and others, 1981). No clear distinctions are apparent on the basis of location (leeward or windward) or land use (undisturbed or mixed use).

Highway Construction Effects in Other Areas

No previous studies of the hydrologic effects of highway construction are available for Oahu or similar central Pacific islands. Investigations in other locations, however, provide some indications of potential effects of road building.

A number of studies have documented streamflow changes attributable to construction of logging roads in the Pacific Northwest region of the United States. These studies showed that significant increases in peak flows resulted from road building in areas where rainfall is the dominant form of precipitation only if roads and other compacted surfaces constituted at least 12 percent of drainage basin area (Harr and others, 1975; Ziemer, 1981, King and Tennyson, 1984).

Several studies have evaluated changes in sediment loads following construction of highways in the eastern United States (table 2). The drainage basins used in these studies included areas previously affected by farming and mining, and do not represent changes from pristine conditions. Results of these studies indicate that the percentage of the annual sediment loads attributable to highway construction ranged from 29 to 85 percent (table 2).

Acknowledgments

Stream-gaging stations 226000, 229000, and 275000 are operated in cooperation with the Honolulu Board of Water Supply. Stream-gaging station 272200 is operated in cooperation with the U.S. Army Corps of Engineers. Stream-gaging station 274499 is operated in cooperation with the Honolulu Department of Public Works. Start and end dates for construction activities were provided by Dennis Higa of the State of Hawaii Department of Transportation. Ground-water withdrawal data were provided by Chester Lao of the City and County of Honolulu Board of Water Supply and Neal Fujii of the State of Hawaii Commission on Water Resource Management.

Table 2. Sediment-load results from previous studies on effects of highway construction effects in the eastern United States

Reference	Annual sediment load from highway construction (percent)	Type of sediment data
Vice and others, 1969	85	total
Eckhardt, 1976	50	suspended
Reed, 1978	29–54	suspended
Helm, 1978	50	suspended
Reed, 1980	63–79	suspended
Ward and Appel, 1988	49	suspended

APPROACH

The approach used in this study is a statistical comparison of data collected before construction with data collected during construction. Data used in this report are daily mean values, unless otherwise noted, and the first day of construction upstream of each gaging station was used to define the periods before and during construction (tables 1 and 3). These periods are not the same at all stations because start dates for data collection and for construction varied. Stream-gaging stations 226200, 270900, 272200, and 275000 have reasonably long periods of data before and during construction (table 3). Stream-gaging station 265600 has only a few days of pre-construction data, and this short period is not sufficient for the analyses described below. Instead, data collected at stream-gaging station 265600 were compared with data collected before construction at nearby stream-gaging station 270900. Suspended-sediment data are available only for 1991 at stream-gaging stations 225800 and 273950, and cannot be used to assess effects of construction at this time. Data for these stations therefore were not considered in this report.

A simple comparison of data collected before and during construction is not adequate because rainfall varied during the study. Streamflow generally increases when rainfall increases, and sediment transport is in part a function of streamflow. Periods with high rainfall tend to have higher streamflow and sediment loads than periods of low rainfall, even in the absence of any construction or other land-use effects.

Statistical procedures used in data analysis were designed to remove the variations in streamflow and suspended-sediment loads that resulted from changes in rainfall. The remaining variability could then be attrib-

Table 3. Pre-construction and construction periods at stream-gaging stations in the H-3 highway study area, Oahu, Hawaii
[Construction was continuing upstream of all stations as of September 30, 1991; station numbers are abbreviated, complete numbers are preceded by 16]

	Pre-construction		During construction	
Station	**Start**	**End**	**Start**	**End**
226200	02/01/83	11/01/87	11/02/87	09/30/91
265600	02/01/83	02/21/83	02/22/83	09/30/91
270900	04/01/84	03/05/89	03/06/89	09/30/91
272200	10/01/81	02/21/83	02/22/83	09/30/91
275000[1]	10/01/82	10/23/88	10/24/88	09/30/91

[1] Sediment data at station 275000 are discontinuous; sediment data are available for 12/01/83 to 09/30/83 and from 07/20/87 to 09/30/91

uted to land-use effects. Effects of rainfall were minimized by using analysis of covariance (Helsel and Hirsch, 1992). Analysis of covariance is a regression-based procedure that assesses relations between two hydrologic variables during different time periods. In this case, the time periods were the periods before and during construction of the H-3 highway ("time period" as used in this report refers to the periods before and during construction listed in table 3). One of the variables, known as the independent variable or covariate, represented natural variations resulting from rainfall, with no effect from highway construction. The other variable is known as the dependent or response variable. The response variable was potentially subject to effects of highway construction. The analysis of covariance tested whether the relation between the covariate and the response variable changed significantly during construction. If a significant change was detected, it was considered the result of a change in drainage-basin conditions that coincided with construction. The applications of this method are described more fully in the sections on streamflow and suspended-sediment analyses below.

Results of statistical tests were reported as significant if the probability of obtaining the results by chance was less than or equal to 5 percent. This is equivalent to setting the α level for all hypothesis tests to 0.05.

Data Collection

Rainfall was recorded using two types of rain gages. At stream-gaging stations 226000, 226200, 265600, and 270900, tipping bucket rain gages were used. At stream-gaging station 275000, a float-type rain gage (8-in. diameter) was used.

Stream-gaging stations 226200, 265600, 270900, 272200, and 275000 were equipped with continuous gage-height recorders. Streamflow was measured periodically at these stations and at miscellaneous sites 265700, 266500, 267500, and 269500 (fig. 2) using standard practices for current-meter measurements (Rantz and others, 1982a). Peak flows that could not be measured with current meters were measured using the slope-area method (Dalrymple and Benson, 1967). Streamflow was computed using the streamflow measurements and gage-height records as described by Rantz and others (1982b).

Suspended-sediment samples were collected at stream-gaging stations using PS-69 automatic suspended-sediment samplers (Edwards and Glysson, 1988). Samples were collected daily when conditions permitted, and more frequently during storms. Depth-integrated cross-sectional samples were collected periodically using the equal-width-increment method (Edwards and Glysson, 1988) and were used to calibrate the PS-69 sample data (Porterfield, 1972). At station 265600, a Manning automatic sampler (Edwards and Glysson, 1988) was used at times in place of the PS-69 because of suspended-sediment deposition near the PS-69 intake. In 1990, the automatic samplers at station 265600 were replaced by an observer who collected daily cross-sectional samples. Cross-sectional samples were collected periodically at miscellaneous sites. Suspended-sediment concentrations were determined at the U.S. Geological Survey laboratory in Honolulu using methods described by Guy (1969). Suspended-sediment loads were computed using suspended-sediment concentrations and streamflow records, as described by Porterfield (1972).

Streamflow Analysis

Streamflow at stream-gaging stations 226200, 270900, 272200, and 275000 was used as the response variable and streamflow at index stream-gaging station 229000 (fig. 2) was used as the covariate in the analysis of covariance. Streamflow at station 229000 was unaffected by H-3 highway construction, diversions, or any major change in land use. Water was withdrawn from tunnels and wells upstream of the station, but these

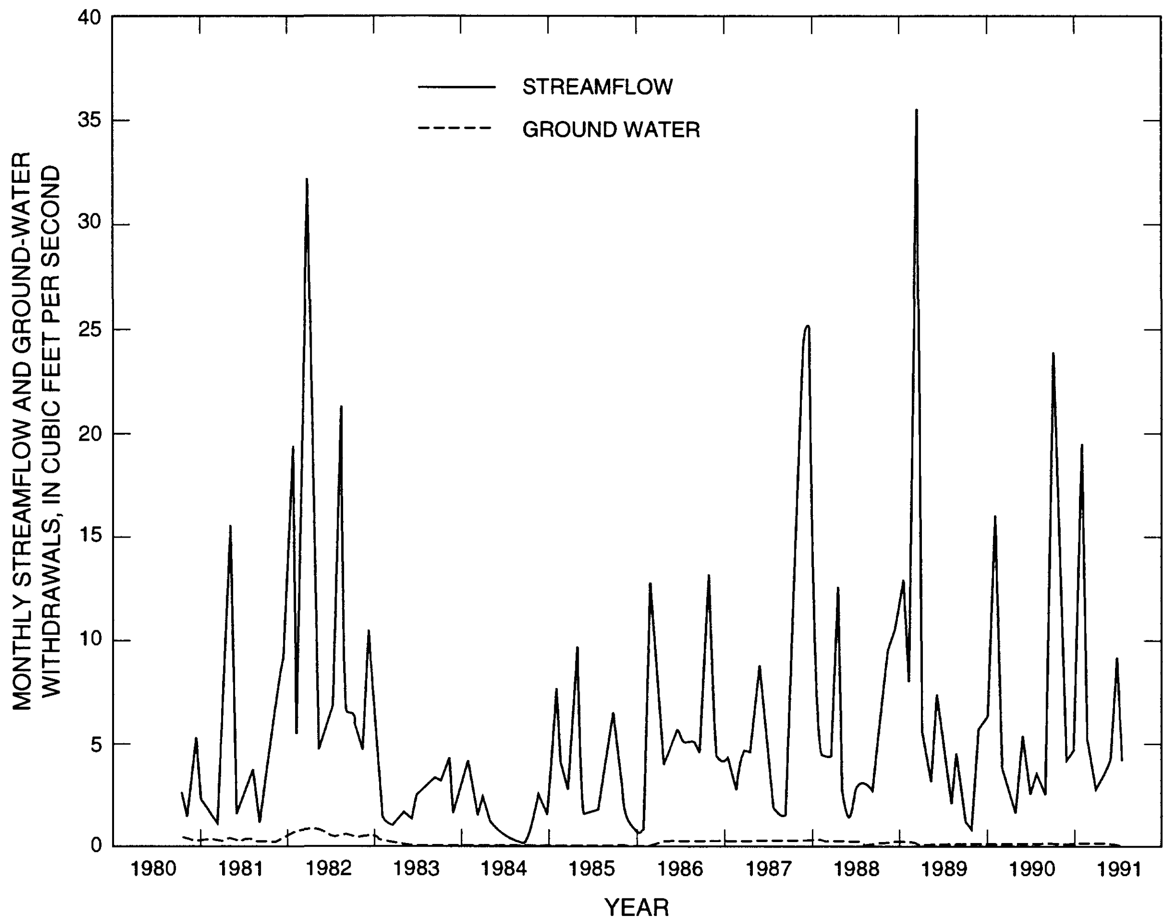

Figure 3. Monthly streamflow at stream-gaging station 16229000 and upstream ground-water withdrawals, Oahu, Hawaii.

withdrawals were small in comparison to streamflow and were nearly constant during the study period (fig. 3). Variations in streamflow at station 229000 were therefore primarily the result of rainfall variations.

Streamflow data were separated into low- and high-flow classes before analysis to permit an evaluation of construction effects on peak flows and base flows. The daily streamflow with an exceedance probability of 10 percent at station 229000, 10.0 ft^3/s, was used to define the low-flow (less than or equal to 10.0 ft^3/s) and high-flow (greater than 10.0 ft^3/s) classes. High-flow data were log-transformed before analysis on the basis of the distributions of regression residuals (Helsel and Hirsch, 1992). Low-flow data were not log-transformed because zero-flow data at station 226200 could not be log-transformed, and because log-transformation did not significantly improve regression relations, as determined by examination of regression residuals.

The analysis of covariance tested whether time period accounted for variations in streamflow at stations 226200, 270900, 272200, and 275000 by comparing three different regression equations relating streamflow at these stations to streamflow at station 229000. One equation, a simple bivariate equation relating the response variable to the covariate, was expressed as

$$Q_{H\text{-}3} = A + (B \times Q_{229000}), \qquad (1)$$

where $Q_{H\text{-}3}$ represented the response variable (daily streamflow at one of the stream-gaging stations 226200, 270900, 272200, and 275000), Q_{229000} represented the covariate (streamflow on the same day at index station 229000), and A and B were regression coefficients. The second equation included, in addition to the covariate, a dummy independent variable, Z, to represent time period. The variable Z was assigned the values of zero for data before construction and 1 for data during construction. This second equation was expressed as

$$Q_{H\text{-}3} = A + (B \times Q_{229000}) + (C \times Z), \qquad (2)$$

where C was a regression coefficient. The coefficient C represented the change in the intercept of the regression relation during construction. The third equation included a third independent variable, an interaction term W. The variable W was computed as the product of Z and streamflow at station 229000. This third equation was expressed as

$$Q_{H\text{-}3} = A + (B \times Q_{229000}) + (C \times Z) + (D \times W), \quad (3)$$

or as

$$Q_{H\text{-}3} = A + (B \times Q_{229000}) + (C \times Z) + (D \times Z \times QW_{229000}), \qquad (4)$$

where D was a regression coefficient. The interaction term was zero for all dates before construction and was equal to the covariate for all dates during construction. The coefficient D represented the change in the slope of the regression relation during construction.

If time period did not significantly affect relations between the response variable and the covariate, a single intercept and slope would adequately describe the relation throughout the study. In such a case, the coefficients for Z and W (C and D) would not be significantly different from zero. If changes in relations between the covariate and the response variable coincided with the beginning of construction, however, either the intercept or the slope or both should differ for the two time periods, and coefficients for Z and/or W would be significantly different from zero.

The significance of the regression coefficient for Z in the equation using all three independent variables (the covariate, Z, and W) was tested using a T-test (for example, Helsel and Hirsch, 1992). A T-statistic is computed as the coefficient for Z divided by its standard error (for example, Iman and Conover, 1983). If this value exceeded the critical T-value for the appropriate degrees of freedom, the coefficient for Z was considered to be significantly different from zero, and the intercept of the regression was considered to be affected by time period.

The significance of the regression coefficient for W and of the combined effect of Z and W were determined with F-tests (for example, Helsel and Hirsch, 1992). F-tests in analysis of covariance are based on regression errors. Regression errors are differences between observed values of the response variable and values estimated by the regression equation corresponding to the same values of the covariate. Errors are in the units of the response variable. If the response variable has been transformed to logarithms, for example, the errors will be in the transformed units. Error sums of squares are the sums of the squares of all regression errors for a regression equation. Mean-square errors are error sums of squares divided by the degrees of freedom for the regression. The standard error is the square root of the mean-square error, and is a measure of average scatter of observed data about the regression line.

F-statistics were used to test the significance of the coefficient for W by comparing the error terms of regressions that included the covariate (streamflow at station 229000), the dummy variable (Z), and the interaction term (W) to those of regressions computed using the covariate and Z as independent variables. F-statistics were computed as the ratio of the difference between the error sums of squares for the two regression relations, divided by their difference in degrees of freedom, to the mean-square error of the regression that included all three independent variables. If the magnitude of the F-statistic exceeded the appropriate critical value of the F distribution (for example, Iman and Conover, 1983), the effect of time period on the slope of the relation between streamflow at the project station and streamflow at the index station was considered to be significant.

F-statistics were similarly used to test the overall significance of time period by comparing the error terms of regressions that included the covariate (streamflow at station 229000), the dummy variable (Z), and the interaction term (W) with those of regressions computed using only the covariate as an independent variable. If the magnitude of the F-statistic exceeded the appropriate critical value of the F distribution (for example, Iman and Conover, 1983), the overall effect of time period on the relation between streamflow at the project station and streamflow at the index station was considered to be significant.

The T-ratios and F-statistics reported for variables Z and W indicate whether changes in intercept and slope individually were significant when both Z and W were included in the regression. Both Z and W can be individually significant, therefore, when the overall effect of time period is not; conversely, the overall effect of time period can be significant when Z and W individually are not.

Suspended-Sediment Analysis

Analysis of covariance was used to assess changes in relations between streamflow and suspended-sediment loads at stream-gaging stations 226200, 270900, 272200, and 275000 during construction of the H-3 highway. The analysis-of-covariance procedure tested whether time period accounted for variations in suspended-sediment loads, after streamflow variations were removed, by computing regression equations relating suspended-sediment load to streamflow. This analysis relied on the implicit assumption that streamflow was not affected by construction. The extent to which this assumption was justified is discussed in this report in the section "Streamflow changes during construction." Time period was again represented by a dummy variable, Z, that took the value of zero for data before construction and 1 for data during construction. An interaction term, W, was computed as the product of Z and streamflow. As described earlier for streamflow, the analysis of covariance compared three regression equations: one using only the covariate as an independent variable, a second including Z, and a third including Z and W.

Streamflow and suspended-sediment data were transformed to common (base 10) logarithms before analysis. A number of daily suspended-sediment loads were reported as 0 tons in two situations: (1) loads were 0 tons on many days at station 226200 when streamflow at that station was 0 ft^3/s; (2) loads were reported as 0 tons at all stations when the product of streamflow, suspended-sediment concentration, and a unit-conversion coefficient was less than 0.005 tons. Loads reported as 0 tons could not be log-transformed. Loads reported as 0 tons on days of no streamflow were not used in the analysis of covariance. Loads reported as 0 tons when their computed values were below 0.005 tons are censored data (unquantified but known to be less than 0.005 tons) and cannot be analyzed with the ordinary least-squares regression normally used in analysis of covariance (Helsel and Hirsch, 1992). Tobit regression (Cohn, 1988) was used in place of ordinary least squares regression to allow the use of censored data. Daily suspended-sediment loads reported as 0 tons for days when streamflow was greater than 0 ft^3/s were assigned an arbitrary value slightly below the reporting limit of 0.005 t/day. Randomly selected subsamples of 500 suspended-sediment load-streamflow data pairs were used for the analysis of covariance to avoid serial correlation of residuals.

The significance of the regression coefficient for Z was tested using a likelihood ratio (Cohn, 1992), which is analogous to the T-test used to evaluate the coefficient for Z in the analysis of streamflow. If the likelihood ratio exceeded the critical value for the appropriate degrees of freedom, the coefficient for Z was considered to be significantly different from zero, and the intercept of the regression was considered to be affected by time period.

F-statistics were used to test the significance of the coefficient for W by comparing the error terms of regressions that included the covariate (streamflow), the dummy variable (Z), and the interaction term (W) to those of regressions computed using the covariate and Z as independent variables. F-statistics were computed as described above for streamflow. If the magnitude of the F-statistic exceeded the appropriate critical value of the F distribution (for example, Iman and Conover, 1983), the effect of time period on the slope of the relation between streamflow and suspended-sediment load was considered to be significant.

F-statistics were used similarly to test the overall significance of time period by comparing the error terms of regressions that included the covariate (streamflow), the dummy variable (Z), and the interaction term (W) to those of regressions computed using only the covariate as an independent variable. If the magnitude of the F-statistic exceeded the appropriate critical value of the F distribution (for example, Iman and Conover, 1983), the overall effect of time period on the relation between streamflow and suspended-sediment load was considered to be significant.

STREAMFLOW BEFORE AND DURING CONSTRUCTION

Hydrologic Conditions During the Study

Rainfall.--Annual rainfall totals were highest at all stations in 1988 and 1989 (table 4). Rainfall at stream-gaging stations 226000, 226200, and 265600 also was high in 1991 (table 4). For much of the H-3 highway study area, therefore, the period of highest rainfall coincided with the construction period (table 3).

Flow duration.--Annual streamflow at all stations was higher in water years 1988, 1989, and 1991 than during the other years of the 1983–91 study period (table 5). Records available for stream-gaging stations 226000 and 272200 show that annual streamflow was higher in 1982 than for any year during the study period. The years of highest streamflow during the study period coincided with years of high rainfall (table 4) and with highway construction at stream-gaging stations 226200, 265600, 270900, and 275000 (tables 1 and 3). Average streamflow per unit area was higher during the pre-construction period than during the construction period at stations 272200 and 275000, and higher during construction at stations 226200 and 270900 (fig. 4).

Flow-duration curves (Searcy, 1959; fig. 5) show the temporal distribution of streamflow for periods before and during construction. Flow-duration curves indicate the percentage of time that values of daily mean streamflow were equalled or exceeded. These curves cannot be used to assess effects of highway construction, because the time periods are not of equal lengths and because rainfall differed during the two periods; however, the curves are useful for evaluating the nature of differences in streamflow during the two periods. At station 226200, low flows persisted longer and peak flows were higher during construction than before construction (fig. 5). At station 270900, the highest daily mean streamflow was during the pre-construction period, but otherwise streamflow was higher during construction. The highest daily mean streamflow at station 272200 was during the construction period, but streamflow was otherwise higher during the pre-construction period. At station 275000, streamflow was greater during the construction period for both low and high flows.

Table 4. Annual rainfall at stream-gaging stations in the H-3 highway study area, Oahu, Hawaii, water years 1983–91

[All values in inches; --, no data; station numbers are abbreviated, complete numbers are preceded by 16]

Water year	Station 226000	226200	265600	270900	275000
1983	65.4	--	--	--	--
1984	44.1	23.5	38.9	--	--
1985	61.6	40.7	63.9	66.8	--
1986	60.9	32.9	59.2	66.2	--
1987	68.3	33.8	67.2	66.7	75.4
1988	90.6	56.5	86.8	95.1	113
1989	[1]91.2	55.5	84.1	87.2	105
1990	66.5	35.3	62.4	62.8	92.0
1991	80.2	41.2	68.5	59.9	--

[1] includes estimated values for period of missing data based on comparison with data at station 226200

Table 5. Annual streamflow at stream-gaging stations in the H-3 highway study area, Oahu, Hawaii, water years 1981–91

[All values are in cubic feet per second-days; --, no data; station numbers are abbreviated, complete numbers are preceded by 16]

Water year	Station 226000	226200	265600	270900	272200	275000
1981	918	--	--	--	3,140	--
1982	4,300	--	--	--	8,040	--
1983	964	--	--	--	4,090	877
1984	517	525	122	--	1,600	520
1985	827	969	284	152	2,290	604
1986	1,590	1,580	406	150	2,940	674
1987	1,440	1,540	612	327	3,760	790
1988	3,140	3,690	988	509	6,070	1,270
1989	3,040	3,640	1,040	532	5,930	1,420
1990	1,670	1,840	532	488	4,280	888
1991	2,740	3,440	762	737	5,000	1,230

Flood frequency.--Recurrence intervals for annual instantaneous peak flows were computed using methods of the Interagency Advisory Committee on Water Data (1981) for two gaging stations in the study area with long (more than 30 years) periods of record: stream-gaging station 226000 in North Halawa Valley (fig. 1) and stream-gaging station 275000 in Haiku Valley (fig. 2). Recurrence intervals for both pre-construction and construction-period annual peak flows at station 226000 ranged from 1 to 2 years. At station 275000, pre-construction recurrence intervals ranged from 1 to 2 years, and all construction-period recurrence intervals were about 2 years. Peak flows during the

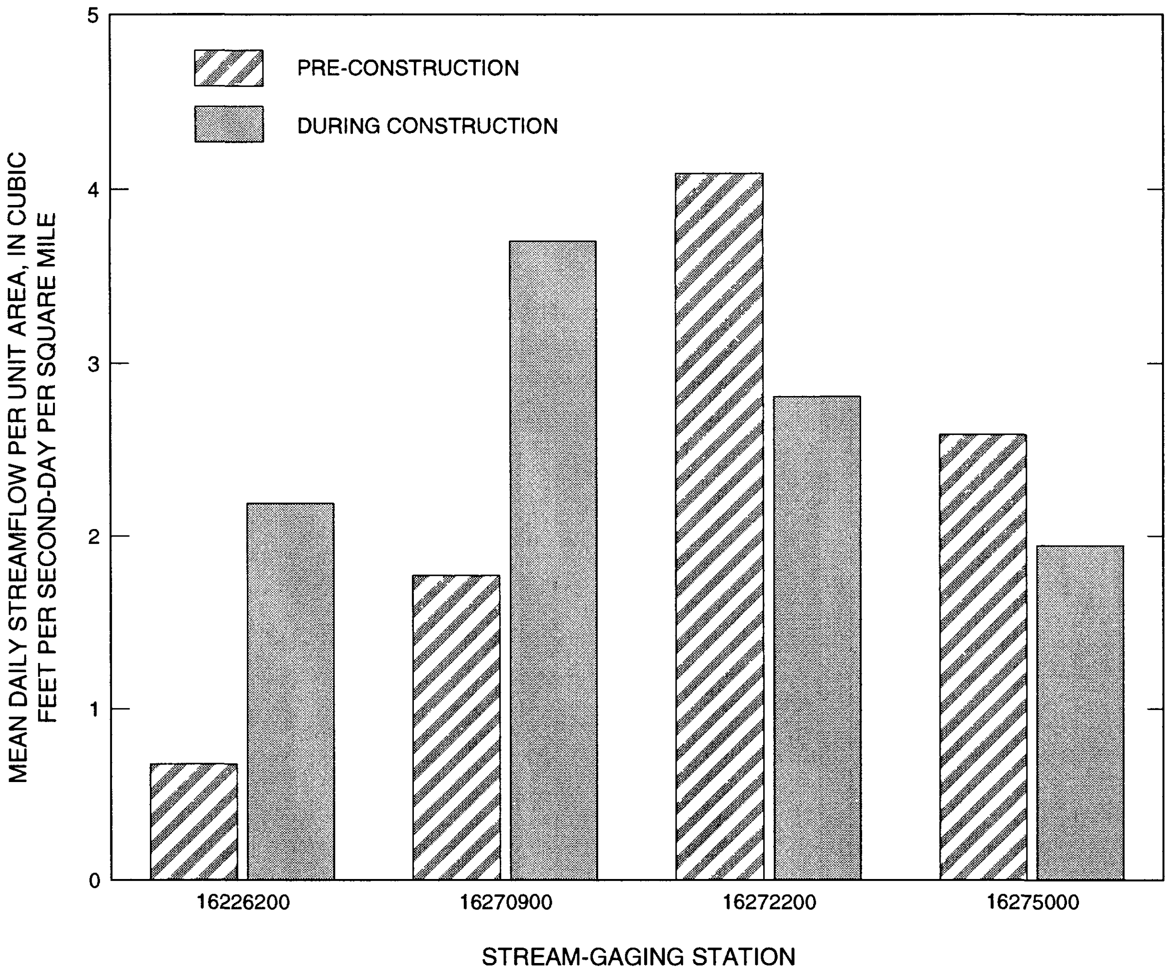

Figure 4. Mean daily streamflow before and during H-3 highway construction at selected stream-gaging stations, Oahu, Hawaii.

study period were therefore not particularly high. The highest peak flows of the 9-year study period (1983–91) were small enough that they recur on average every 2 years.

No long-term records are available for flood-frequency analyses in the Kamooalii drainage basin, but records at nearby stream-gaging station 274499 (fig. 2) indicate that recurrence intervals between 1981 and 1991 ranged from about 1 year in 1983 to 4 years in 1982. The second highest peak was in 1987, with a recurrence interval of 3 years, and the third highest peak was in 1990, with a similar recurrence interval. Peak flows during the study period therefore were moderate in the vicinity of the Kamooalii drainage basin, and did not differ much between pre-construction and construction periods.

The highest annual peak flow of the study period at station 226000 was recorded during construction, in 1991. The second-highest peak flow was in 1988, also during construction. At station 275000 the two highest peak flows occurred before construction in 1988 and 1987, respectively. Streamflow peaks at stations 265600, 270900, and 272200 were highest in 1987 and 1988 (U.S. Geological Survey, 1982; Chinn and others, 1983, 1984, 1985, 1986, 1988; Nakahara and others, 1988, 1989; Matsuoka and others, 1991, 1992). The highest streamflow peaks of the study period, therefore, were during construction at stations 265600 and 272200 and before construction at station 270900.

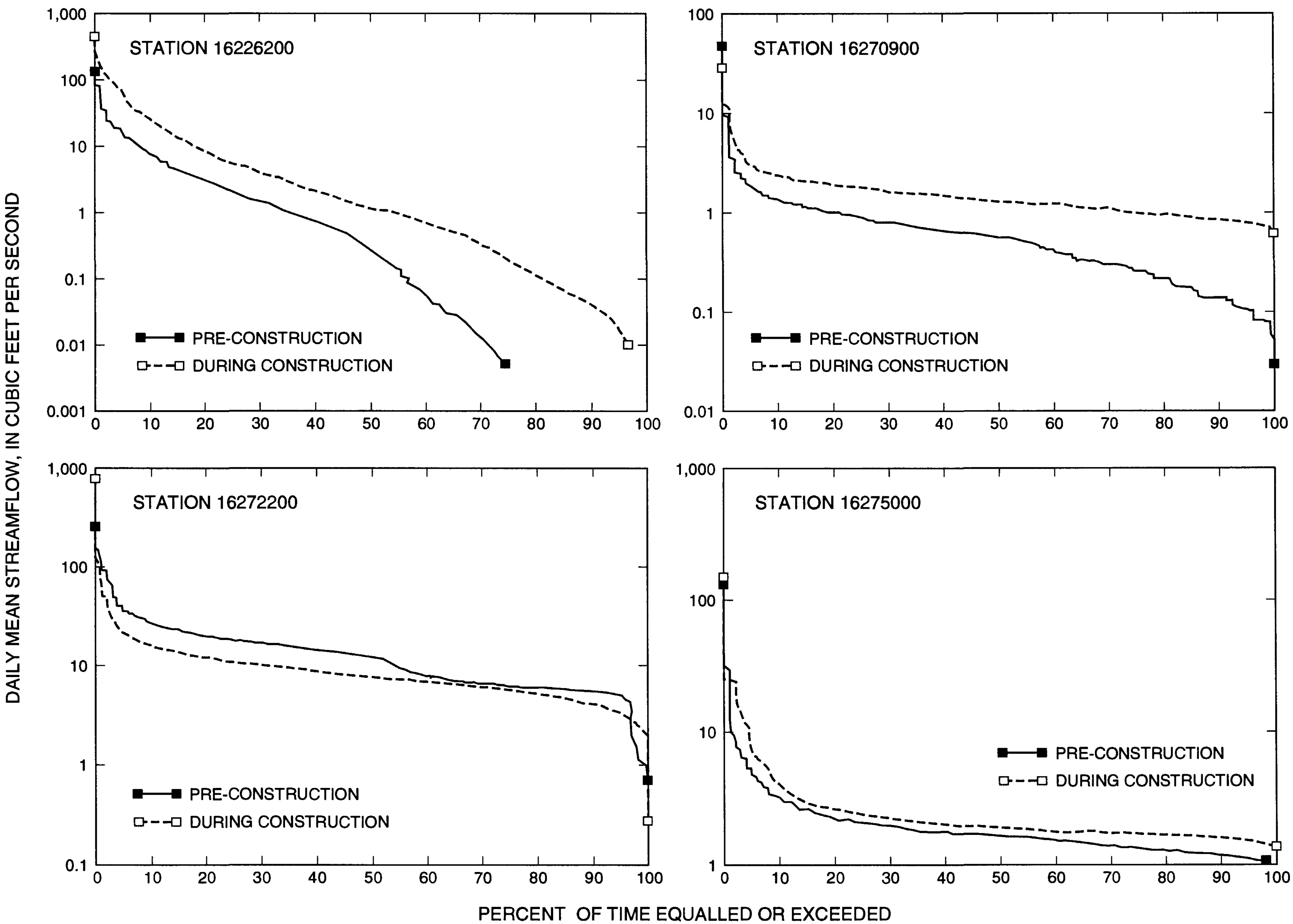

Figure 5. Flow-duration curves of daily mean streamflow at selected stream-gaging stations, Oahu, Hawaii.

Table 6. Analysis of covariance relating streamflow at index station to streamflow at stream-gaging stations in the H-3 highway study area, Oahu, Hawaii

[Daily mean streamflows at station 229000 and at stations 226200, 270900, 272200, and 275000 were used as the covariate and response variables, respectively; Z was set to zero for pre-construction and 1 for construction; W was set to Z × streamflow at station 229000; high-flow data were log-transformed; * indicates significant effect of period on the basis of T-ratio or F- test; critical T-ratio is 1.96; critical F values are 3.84 for significance of W and 3.00 for significance of Z and W together; station numbers are abbreviated, complete numbers are preceded by 16]

Station	Regression coefficients for				T-ratio for significance	F-statistics for significance of	
	Intercept	Slope	Z	W	of Z	W	Z + W
Low flow (streamflow less than or equal to 10.0 ft³/s at station 229000)							
226200	-1.43	1.17	-0.431*	0.0142	-2.33*	0.08	6.67*
270900	0.274	0.0988	0.665*	0.0154*	24.5*	4.92*	1,160*
272200	5.15	2.07	-0.325	-0.979*	-1.31	208*	344*
275000	1.29	0.154	0.316	0.0545*	0.62	17.6*	37.4*
High flow (streamflow greater than 10.0 ft³/s at station 229000)							
226200	0.166	0.891	-0.401*	0.313*	-2.10*	4.88*	2.48
270900	-0.880	0.849	0.399*	-0.176	3.05*	3.53	16.8*
272200	0.582	0.644	-0.321*	0.149	-2.95*	3.74	13.2*
275000	-0.544	0.913	0.004	0.0654	0.030	0.487	5.50*

Streamflow Changes During Construction

Annual streamflow records used for this report were rated as "good," "fair," or "poor" (Matsuoka and others, 1992). Records rated as "good" are considered to have 95 percent of the published daily values within 10 percent of their true values. Records rated as "fair" are considered to have 95 percent of the published daily values within 15 percent of the true values. Records rated as "poor" are less accurate than "fair" records. On the basis of the annual ratings of streamflow records for stations used in this report, daily mean values of streamflow for the entire study period were considered accurate to within 15 percent at stream-gaging stations 226200, 265600, 270900, and 275000, and to within 10 percent at stream-gaging stations 272200 and 229000. Streamflow changes that are within these accuracy limits cannot be considered hydrologically significant, although they may be statistically significant.

Low flows.--The changes in regression intercepts and slopes shown in table 6 indicate the direction and magnitude of changes in streamflow during construction. Changes in intercepts, which are equal to the coefficients for variable Z listed in table 6, are constants that increase (positive coefficients) or decrease (negative coefficients) flows estimated with the regression equation equally over the entire range of data. Changes in slope, which are equal to the coefficients for variable W listed in table 6, result in changes in estimated streamflow that are proportional to streamflow at stream-gaging station 229000.

Relations between low flows at stream-gaging stations 226200, 270900, 272200, and 275000 and low flows at stream-gaging station 229000 changed significantly during construction (table 6). Regression intercepts were significantly different at stations 226200 and 270900; the intercept decreased at station 226200 and increased at station 270900. Regression slopes were significantly different at stations 270900, 272200, and 275000; slope increased at stations 270900 and 275000, and decreased at station 272200. Standard errors for pre-construction regressions were 2.40 ft^3/s at station 226200, 0.32 ft^3/s at station 270900, 5.10 ft^3/s at station 272200, and 0.54 ft^3/s at station 275000.

To determine if the low-flow changes detected using analysis of covariance were hydrologically significant, changes in low flows were estimated by applying pre-construction regression coefficients for slope and intercept from the analysis of covariance (table 6) to construction-period low flows at station 229000. The estimated low flows represent low flows that would be expected if relations between flows at H-3 project stations 226200, 270900, 272200, and 275000 and the index station 229000 were unchanged from pre-construction conditions (table 7). The differences between observed and estimated low flows during construction are estimates of changes resulting from factors other than rainfall variations, since the analysis of covariance

Table 7. Estimated changes in streamflow resulting from altered drainage-basin conditions during H-3 highway construction, Oahu, Hawaii

[Estimated streamflows were computed by applying pre-construction regression coefficients listed in table 6 to daily mean streamflows at station 229000 during the construction period; differences were computed as observed streamflow less estimated streamflow; percent differences were computed as differences divided by the estimated streamflow and multiplied by 100; all streamflow data are sums of daily mean streamflows and are in cubic feet per second-days (ft^3/s-d); <, less than; station numbers are abbreviated, complete numbers are preceded by 16]

Station	Construction-period streamflow		Difference	Difference (percent)
	Observed	Estimated		
Low flow (streamflow less than or equal to 10.0 ft^3/s at station 229000)				
226200	2,800	3,260	–460	–14
270900	1,090	502	588	117
272200	23,000	32,100	–9,100	–28
275000	1,920	1,710	210	12
High flow (streamflow greater than 10.0 ft^3/s at station 229000)				
226200	2,270	2,300	–30	–1
270900	488	456	32	7
272200	5,150	5,140	10	<1
275000	1,280	1,150	130	11

procedure accounts for the effects of rainfall by using streamflow at the index station as a covariate. Estimated changes range from a decrease of 28 percent of estimated low flows at station 272200 to an increase of 117 percent at station 270900 (table 7). Only the estimated changes at stations 270900 and 272200 were greater than the limits of accuracy for the streamflow records used in the analyses. The estimated changes for stations 226200 and 275000 are within accuracy limits and therefore cannot be considered hydrologically significant.

High flows.--Relations between high flows at stream-gaging stations 270900, 272200, and 275000 and high flows at index stream-gaging station 229000 changed significantly during construction (table 6). The intercept increased at station 270900 and decreased at station 272200. Neither Z nor W were significant individually at station 275000, but their combined effect was significant. No significant changes in high flows were detected for station 226200, although both Z and W were significant variables individually if both were included in the regression.

Changes in high flows resulting from altered drainage-basin conditions during highway construction were estimated in the same manner as described for low flows. Estimated high flows were back-transformed from logarithmic units and adjusted for bias using the nonparametric method of Duan (1983). Bias-correction factors ranged from 1.12 to 1.24. Standard errors, in log units, ranged from 0.214 to 0.286.

Estimates of changes in high flows required extrapolation of the pre-construction regression beyond the range of pre-construction data at stations 226200, 272200, and 275000. The use of these estimates requires the assumption that the pre-construction relation between streamflow at index station 229000 and streamflow at H-3 project stations 226200, 270900, 272200, and 275000 remains linear at flows higher than any observed during the pre-construction period. To check this assumption, annual streamflow at station 229000 was compared with annual streamflow at station 226000 for the period 1954–87 and to annual streamflow at station 275000 for the period 1960–76 using double-mass curves (Searcy and Hardison, 1960). These periods included higher annual streamflows than the 1983–91 study period. No deviations from a generally linear pattern were detected, and the extrapolation was considered reasonable for station 275000 and for station 226200, which is about 1 mi downstream of station 226000. No long-term data are available to test the validity of the assumption for station 272200; changes estimated for this station should be considered less reliable than those for other stations.

Changes in high flows ranged from a decrease of 1 percent at station 226200 to an increase of 11 percent at station 275000 (table 7). All of these estimated changes are within the accuracy limits for streamflow records, and cannot be considered hydrologically significant.

Streamflow at stream-gaging station 265600.--Only a few days of pre-construction data were available for stream-gaging station 265600. A meaningful comparison of pre-construction and construction data could not be made with so few pre-construction data. Instead, construction effects on streamflow at stream-gaging station 265600 were assessed by comparing construction-period streamflow data at this station to pre-construction data for the same days at nearby stream-gaging station 270900 using the Wilcoxon signed-ranks test (Iman and Conover, 1983). Streamflow data were divided by drainage basin areas to allow direct comparison of data for the two stations.

Station 270900 was used for the comparison because of its proximity to station 265600, which would tend to eliminate natural sources of streamflow variability. The Luluku drainage basin upstream of station 270900, however, is entirely within the marginal dike zone where large quantities of high-level ground water are discharged to streams. In contrast, the drainage basin upstream of station 265600 is mostly within the dike complex where ground-water discharge is generally low (Takasaki and Mink, 1985). Base flows could be expected to be higher at station 270900 than at station 265600 because of this difference in geology. Although comparison of streamflow data for these two stations is of limited value, it is useful to the extent that large increases in streamflow at station 265600 during highway construction might be detected if streamflow at station 265600 was found to be higher than streamflow at station 270900.

Daily mean streamflows per unit area at station 265600 were significantly ($p<0.0001$) lower than those at station 270900 under pre-construction conditions. Average streamflow per unit area at station 265600 was 1.37 $(ft^3/s)/mi^2$ and average streamflow per unit area at station 270900 was 1.78 $(ft^3/s)/mi^2$. The significant difference between streamflow per unit area at these stations was likely the result of differences in geology. Large increases in streamflow during construction at station 265600 appear unlikely because construction period streamflow at station 265600 was lower than pre-construction streamflow at station 270900. Any streamflow decreases resulting from construction cannot be detected with this procedure.

Land-Use Effects on Streamflow

Changes in streamflow during highway construction resulting from factors other than changes in rainfall were significant at stations 270900 and 272200 (tables 6 and 7). These changes are unlikely to have occurred as a result of random streamflow variations, and are probably the result of changes in drainage-basin conditions because of land-use activities. H-3 highway construction is a possible cause of the changes in streamflow, but other activities that coincided with construction may have also affected streamflow.

Low Flows

Low flows are maintained by ground-water discharge in the study area (Takasaki and others, 1969; Izuka, 1992). Any alterations of the ground-water flow system could have affected low flows (Hirashima, 1963; 1965; 1971), which changed significantly during construction at stream-gaging stations 270900 and 272200. The most likely activities that could have affected ground-water flow during construction of the H-3 highway include municipal ground-water withdrawals and H-3 construction.

Municipal ground-water withdrawals.--Municipal ground-water withdrawals from tunnels and wells represent the largest development of ground water in the study area (Takasaki and Mink, 1985). Municipal withdrawals increased significantly ($p<0.05$) during highway construction in the drainage basins upstream of stream-gaging stations 270900 and 272200 (fig. 6). These increased withdrawals could be expected to reduce low flows at these stations (Takasaki and Mink, 1985).

Stepwise multiple regression analyses (Helsel and Hirsch, 1992) using monthly average streamflow at stream-gaging station 229000, monthly precipitation (from Wong and Hill, 1992, and U.S. Geological Survey unpublished data), and monthly average municipal ground-water withdrawals (Honolulu Board of Water Supply, 1981–92) as independent variables failed to detect any significant effects of withdrawals on monthly average streamflow at station 272200. Withdrawals were a significant explanatory variable at station 270900, but were positively correlated with streamflow. A negative correlation would be expected if withdrawals were depleting streamflow. On the basis of these analyses, no clear link between municipal withdrawals and streamflow is apparent.

A simple comparison of withdrawals and streamflow, however, could fail to detect effects of withdrawals on streamflow if interrelations are complicated by seasonal or other variations. For example, the proportion of ground water currently withdrawn from wells and tunnels that would be discharged to streams under natural conditions might change from month to month, or from wet season to dry season. In such a case, total withdrawals would be poorly correlated with streamflow even if streamflow was affected by withdrawals.

Although the true proportion of the ground water withdrawn for municipal uses that would otherwise have supplied streamflow cannot be determined with any certainty, a rough estimate of the maximum potential effect of increased withdrawals during highway

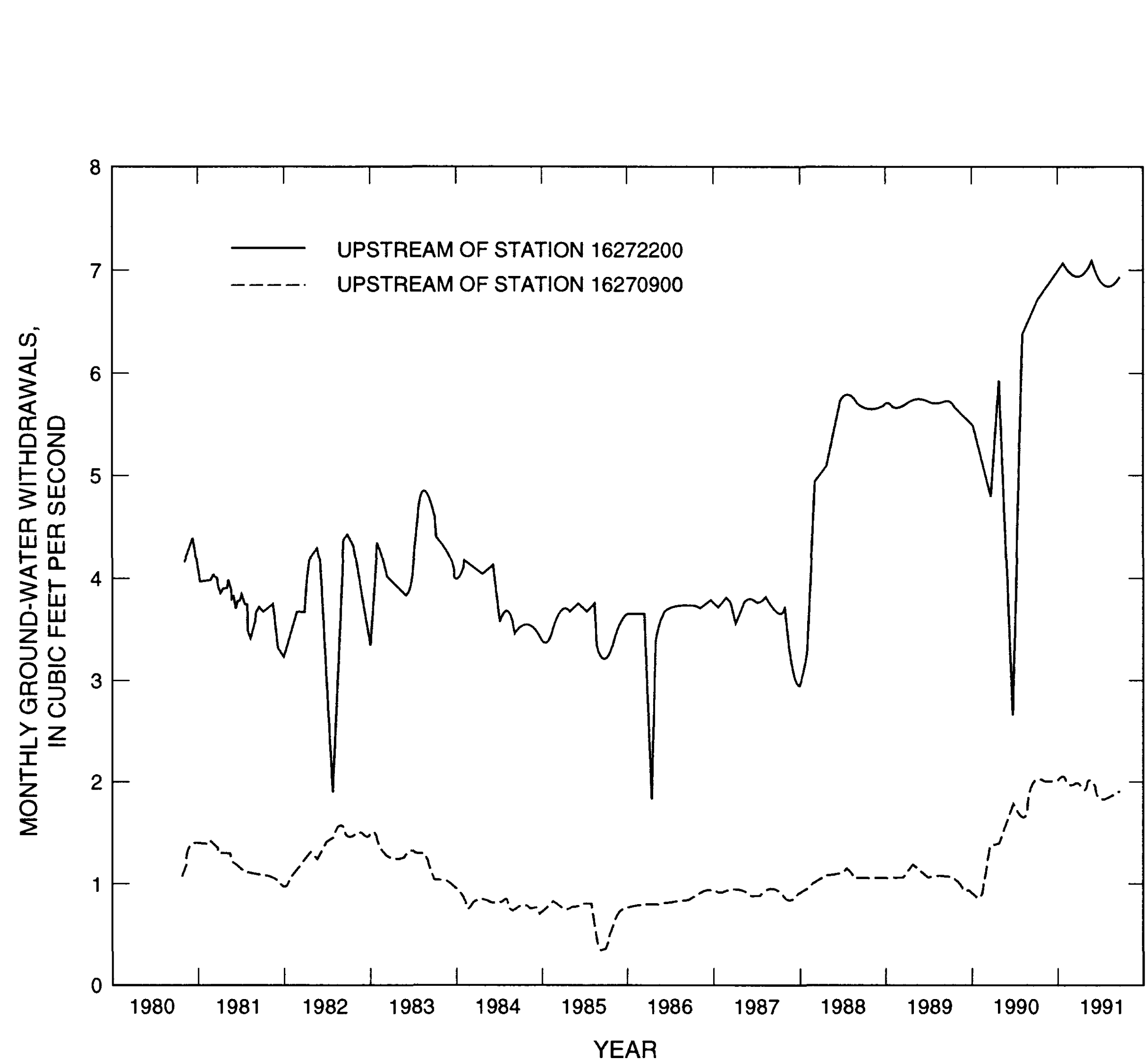

Figure 6. Monthly ground-water withdrawals upstream of stream-gaging stations 16272200 and 16270900, Oahu, Hawaii.

construction can be computed using Board of Water Supply pumping data (Honolulu Board of Water Supply, 1981 through 1992). Average rates of ground-water withdrawals were computed for the pre-construction and construction periods at station 272200. The pre-construction average was 3.8 ft^3/s and the construction-period average was 4.7 ft^3/s. The difference between these two averages, 0.9 ft^3/s, was multiplied by the 3,143 days in the construction period at station 272200 to obtain an estimate of 2,829 ft^3/s-d that potentially could have been diverted from the stream by increased municipal withdrawals. This estimate is equivalent to 31 percent of the estimated decrease in low flows at station 272200 during construction (table 7). This analysis requires the assumption that all of the water attributed to increased municipal withdrawals would otherwise have flowed to the stream. The actual proportion was probably less, and the true effect of increased municipal withdrawals on low flows at station 272200 was probably less than the estimated decrease of 2,829 ft^3/s-d. However, because municipal ground-water withdrawals increased upstream of station 272200 coincident with an apparent decrease in low flows at that station (tables 6 and 7), some of the decrease in low flows may be attributable to the increased withdrawals.

Although municipal withdrawals increased significantly ($p<0.05$) in the drainage basin upstream of station 270900 during construction, low flows increased. Any effects of increased withdrawals on low flows at this station were apparently less than other effects that increased low flows. One such possible effect is discussed in this report in the section "H-3 highway construction."

Ground water also was withdrawn from two wells upstream of station 265600 beginning in March, 1990

(Neal Fujii, State of Hawaii Department of Land and Natural Resources, Commission on Water Resource Management, written commun., 1993). These wells were used to irrigate the new Minami golf course (fig. 2). The combined average monthly withdrawal of these wells from March, 1990 to September, 1991 was about 0.13 Mgal/d, equivalent to 0.20 ft^3/s. This average is equivalent to about 12 percent of the average daily streamflow at station 265600 and about 2 percent of the average daily streamflow at station 272200 (Matsuoka and others, 1992). No significant effect from pumping golf-course wells was detected using analysis of covariance with monthly streamflow data at station 265600. Pumping of ground water for golf-course irrigation does not appear to have had a major effect on streamflow at stations 272200 and 265600.

Ground water in the marginal dike zone of windward Oahu can flow from one drainage basin to another between parallel dikes (Takasaki and Mink, 1985). Wells and water-development tunnels can change the location of ground-water divides and divert water from one valley to another, as shown by Hirashima (1963). Changes in withdrawals within or outside the study area may have affected ground-water flow systems to the extent that ground water was transferred from one drainage basin to another. An evaluation of this scenario is beyond the scope of this report.

H-3 highway construction.--H-3 highway construction involves excavation of highway tunnels in a ground-water recharge zone below the crest of the Koolau Range and clearing, cutting, filling, compacting, and paving of the land surface in and near areas of ground-water discharge. These activities could potentially affect low flows that are maintained by ground-water discharge.

Seepage of ground water into the trans-Koolau exploratory tunnel was estimated to less than 30 gal/d by Jackson and Multhaup (1990). The estimated flow rate is equivalent to only 0.00005 ft^3/s. Maximum seepage rates for the exploratory tunnel after heavy rain were estimated to be 10 gal/h per 100-ft section, roughly equivalent to 0.02 ft^3/s for the entire tunnel. Field observations by USGS personnel also indicated very small quantities of seepage into the exploratory tunnel. Water seeping from the roof and walls of the tunnel later infiltrated the floor of the tunnel (Jackson and Multhaup, 1990), and was not discharged from the tunnel portals as surface water. The trans-Koolau tunnels, therefore, have probably had a minor effect on streamflow in the study area.

Removal of vegetation during highway construction could have resulted in decreased evapotranspiration and hence an increase in the volume of water available to maintain low flows. Before highway construction, much of the drainage basin upstream of station 270900 was planted in bananas. During construction, banana trees covering about 6 percent of the drainage basin were removed and part of the former plantation was covered with loose rock fill. This unvegetated rock fill probably reduced evapotranspiration from these areas to a fraction of the pre-construction rate. Potential evaporation is about 62 percent of pan evapotranspiration in humid areas of Oahu (Shade, 1984). Pan evaporation at Maunawili Ranch (fig. 1) was about 3.6 ft/yr over an 11-year period (State of Hawaii Department of Land and Natural Resources, 1973), and potential evapotranspiration was about 2.2 ft/yr. If evapotranspiration equal to 2.2 ft/yr were eliminated over the 11 percent of the drainage basin directly affected by the H-3 highway, 0.09 ft^3/s of additional water would be available to augment streamflow. Over the 1,800-day construction period, reduced evapotranspiration would result in an additional 165 ft^3/s-d of streamflow, equal to 28 percent of the estimated increase in low flows at station 270900 (table 7). Increased low flows also may have resulted in part from irrigation for highway landscaping and reduced agricultural streamflow diversions.

Reduced evapotranspiration may have affected streamflow at station 272200, where the combined area used for H-3 highway and golf course construction was about 12 percent of total drainage basin area. Low flows decreased during construction (table 7), however, indicating that effects of increased ground-water withdrawals or other effects that decreased low flows were apparently greater. Compaction of soil during highway and golf-course construction may have reduced infiltration and decreased the amount of water available to sustain low flows.

High Flows

Previous studies of the effects of roadbuilding on streamflow have focused on increases in streamflow peaks because of compaction of soil and increases in impervious areas (Harr and others, 1975; Ziemer, 1981; King and Tennyson, 1984). These effects appear to have been minor in the H-3 highway study drainage basins (table 7). Studies in areas where rainfall is the most important form of precipitation have reported that effects of roadbuilding on peak flows were detectable only when 12 percent or more of drainage basin area was affected (Ziemer, 1981). The H-3 highway affected between 3 and 11 percent of drainage basin areas upstream of the stream-gaging stations used for this study, and the apparent lack of any major effects of H-3 construction on high flows may have resulted in part from the relatively small areas affected by the highway.

SUSPENDED-SEDIMENT LOADS BEFORE AND DURING CONSTRUCTION

Annual suspended-sediment loads were generally low during 1983–86 (table 8), when rainfall and streamflow were low. Suspended-sediment loads were high during 1988–91 when rainfall and streamflow were high and after construction had begun upstream of all stations. The highest annual load at stream-gaging station 272200 was in 1982 (table 8).

Suspended-sediment yields were computed for pre-construction and construction periods by dividing daily loads by drainage basin areas. Mean daily suspended-sediment yields were higher before construction at stream-gaging stations 270900 and 272200, and higher during construction at stream-gaging stations 226200 and 275000 (fig. 7).

Sediment duration.--Sediment-duration curves (Searcy, 1959) are analogous to flow-duration curves; each value of daily mean suspended-sediment load is plotted against the percentage of time that the load is equalled or exceeded. Sediment-duration curves (fig. 8) indicate increased and more persistent suspended-sediment transport during construction at stream-gaging stations 226200, 270900, and 275000, although the highest daily suspended-sediment load at station 270900 was during the pre-construction period. The sediment-duration curve for station 272200 indicates decreased suspended-sediment transport during construction.

Relations Between Streamflow and Suspended-Sediment Loads

The analysis of covariance procedure requires that the covariate, streamflow, be independent of the factor represented by the dummy variable, in this case construction. The lack of any significant effects on high flows at stream-gaging stations indicates that this condition was reasonably fulfilled.

Table 8. Annual suspended-sediment loads at stream-gaging stations in the H-3 highway study area, Oahu, Hawaii

[All values are in tons; --, no data; station numbers are abbreviated, complete numbers are preceded by 16]

Water year	Station number				
	226200	265600	270900	272200	275000
1981	--	--	--	723	--
1982	--	--	--	3,210	--
1983	--	--	--	173	--
1984	31	24	--	77	--
1985	314	541	43	336	--
1986	362	472	91	322	--
1987	615	631	402	1,190	--
1988	3,500	1,730	485	2,240	1,310
1989	16,600	1,220	180	1,290	3,400
1990	2,260	1,160	53	593	1,660
1991	5,220	512	333	1,270	2,970

Analysis of covariance results indicate that relations between streamflow and suspended-sediment loads changed significantly during construction at stream-gaging stations 226200, 270900, and 275000 (table 9; fig. 9). Regression slopes increased during construction at all three stations. The regression intercept increased during construction at station 226200, and intercepts decreased during construction at stations 270900 and 275000 (table 9).

Changes in regression coefficients indicate how streamflow-sediment relations were affected during construction. The increases in both slope and intercept at station 226200 indicate that suspended-sediment loads increased relative to streamflow during construction. This increase affected the entire range of streamflow at this station except for flows below 0.21 ft^3/s. As a result of the increase in slope, the construction regression line is actually below the pre-construction regression line for flows less than 0.21 ft^3/s. Because very little sediment is transported at such low flows, the intersection of the regression lines is not significant in assessing the effects of construction on sediment loads. At station 270900, the increased slope and decreased intercept (fig. 9) cause the pre-construction and construction regression lines to intersect; the intersection point, in units of log-transformed streamflow, can be determined by dividing the absolute value of the coefficient for Z by the coefficient for W. The two regressions estimate the same suspended-sediment load for a streamflow of 1.25 ft^3/s. Suspended-sediment loads are

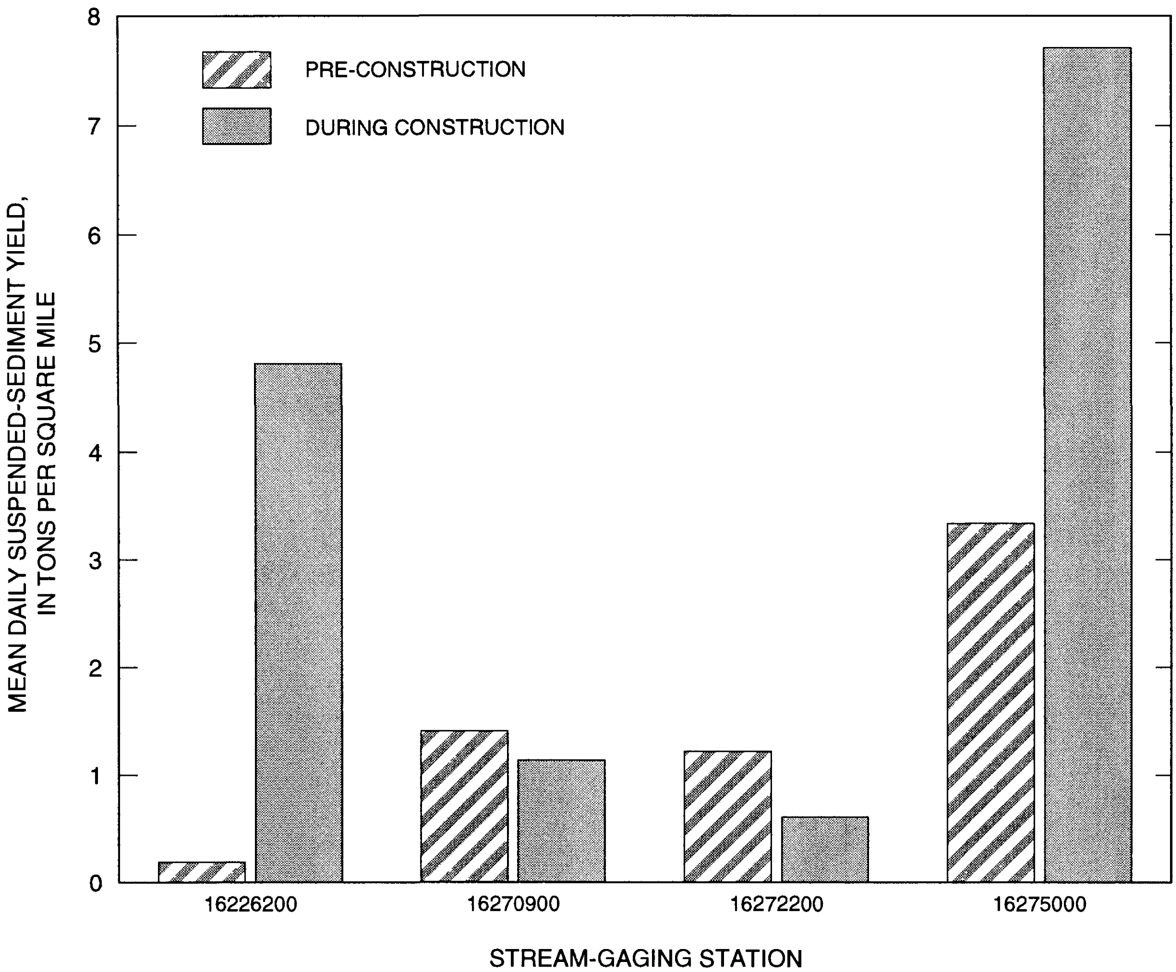

Figure 7. Mean daily suspended-sediment yield before and during H-3 highway construction at selected stream-gaging stations, Oahu, Hawaii.

Table 9. Analysis of covariance for suspended-sediment loads at stream-gaging stations in the H-3 highway study area, Oahu, Hawaii

[Common logarithms of daily mean streamflow and suspended-sediment load were used as the covariate and response variable, respectively; Z was set to zero for pre-construction and 1 for construction; W was set to Z × log-streamflow; tobit regression (Cohn, 1988) was used to compute F-statistics; * indicates significant effect of period on the basis of F-test; critical F-values are 3.84 for significance of W and 3.00 for significance of Z and W together; station numbers are abbreviated, complete numbers are preceded by 16]

Station	Regression coefficients for				Likelihood ratio for Z	W	F-statistic for significance of (Z +W)
	Intercept	Slope	Z	W			
226200	-1.59	0.656	0.311*	0.456*	26.3*	43.6*	29.8*
270900	-1.62	1.05	-0.175*	1.80*	13.0*	92.2*	46.6*
272200	-1.98	1.43	-0.069	0.140	0.18	1.79	2.96
275000	-2.32	2.69	-0.167*	0.599*	8.57*	12.3*	7.18*

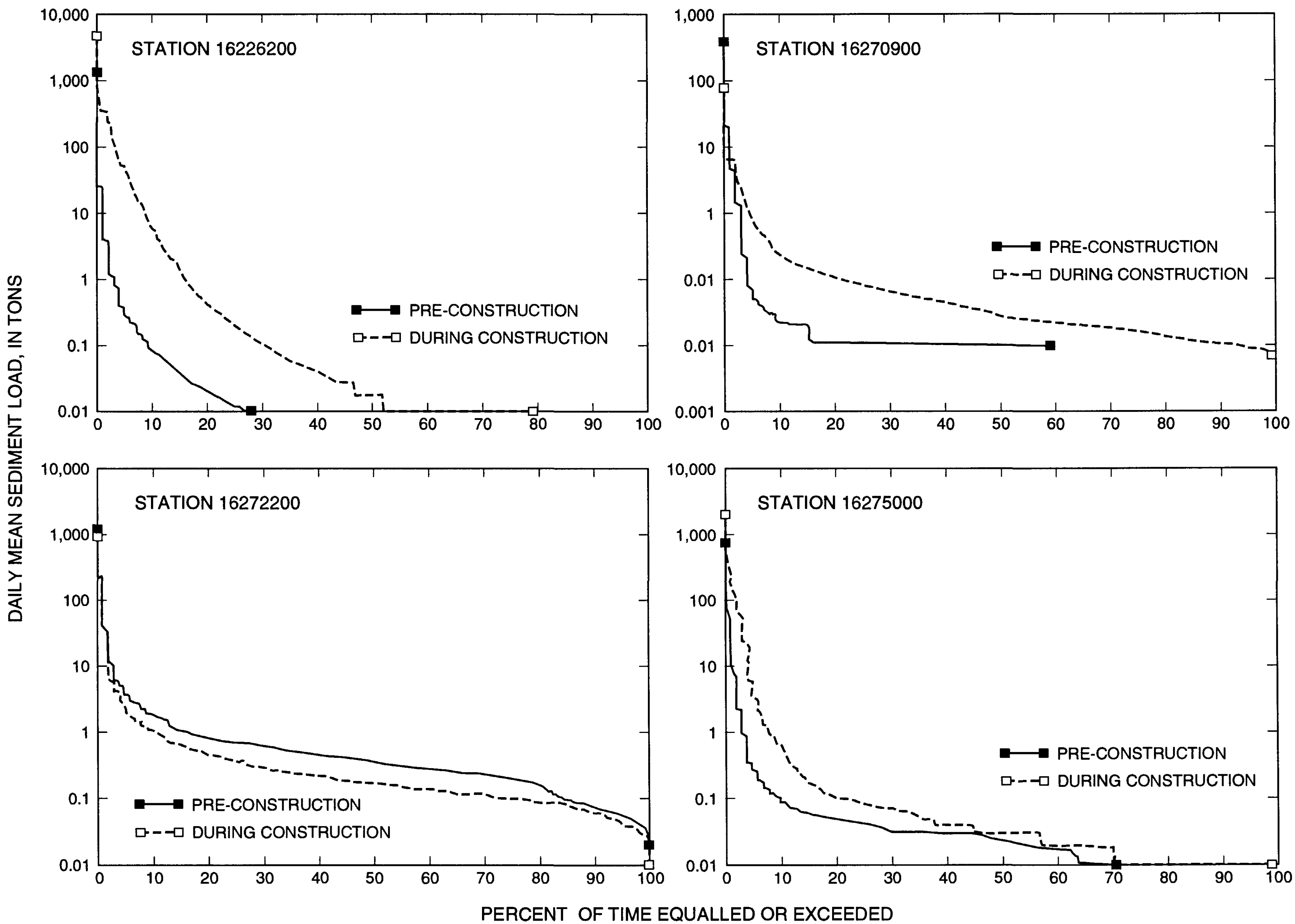

Figure 8. Sediment-duration curves of daily mean sediment load at selected stream-gaging stations, Oahu, Hawaii.

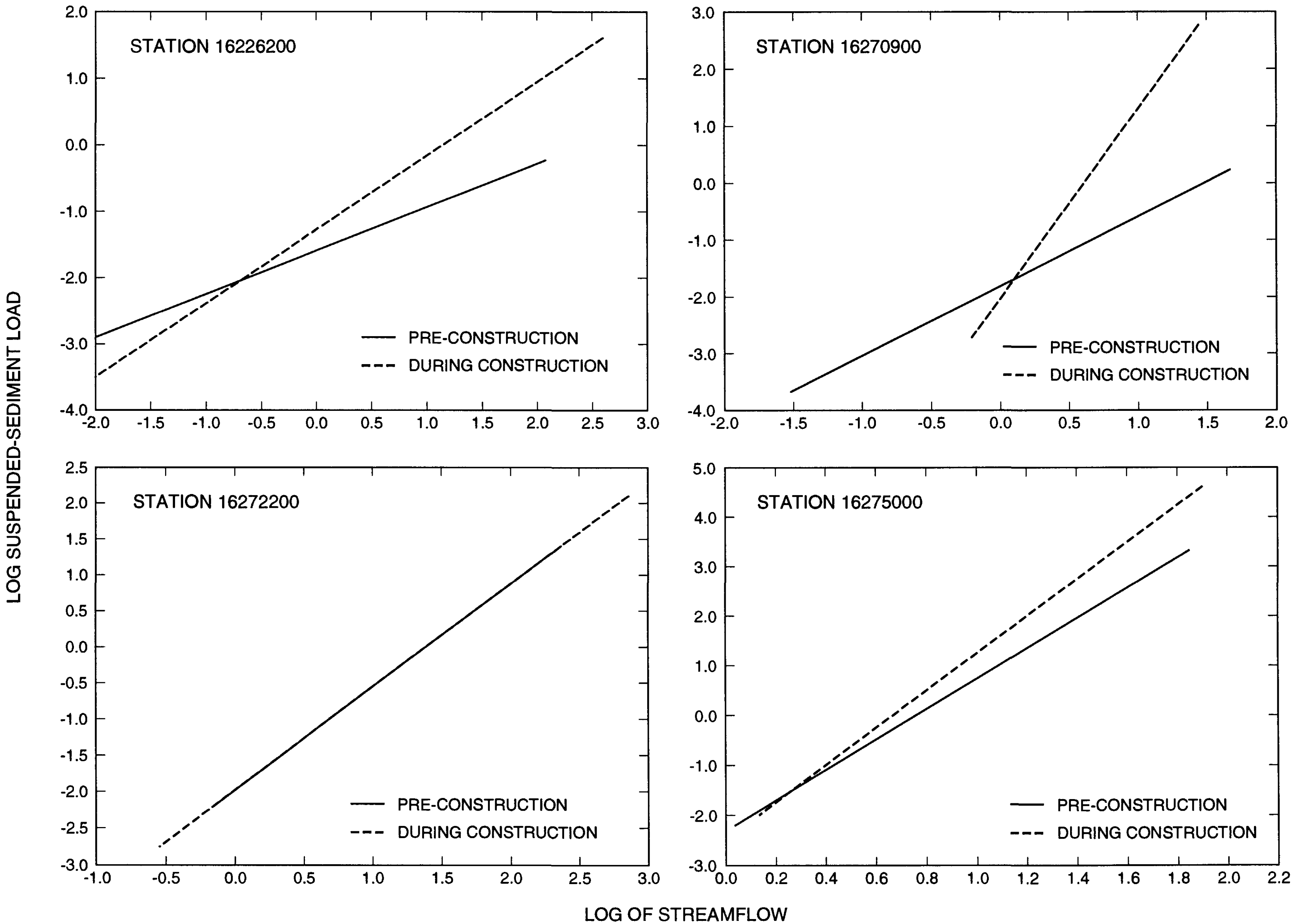

Figure 9. Pre-construction and construction-period relations between streamflow and suspended-sediment loads at selected stream-gaging stations, Oahu, Hawaii.

estimated to be higher before construction for streamflows below 1.25 ft^3/s and higher during construction for streamflows higher than 1.25 ft^3/s. This is also the case at station 275000, where estimated loads corresponding to streamflows less than 1.90 ft^3/s are higher before construction and loads at streamflows higher than 1.90 ft^3/s are higher during construction (fig. 9). Because most of the suspended-sediment loads are transported at flows higher than these intersection points, the estimated changes in streamflow-sediment relations at stations 270900 and 275000 would be expected to indicate that loads increased during construction.

The significance of the changes in regression slope and intercept detected for station 270900 (table 9; fig. 9), however, are difficult to reconcile with the lower average suspended-sediment yield observed during construction, particularly because streamflow was higher during construction, and higher streamflow would normally increase sediment loads. Examination of scatterplots of daily suspended-sediment loads and corresponding daily mean streamflows revealed that several low outliers were affecting streamflow-sediment relations. Analysis of covariance with ordinary least squares regression using loads of 0.5 t/d or greater and corresponding streamflows indicated that suspended-sediment loads in this range actually decreased during construction; this effect was masked by the inclusion of the loads less than 0.5 t/d in the original analysis of covariance. The omission of loads below 0.5 t/d eliminates only 4 percent of the suspended-sediment load for the period of record at station 270900 from the analysis. The changes in regression coefficients for station 270900, although statistically significant, do not represent substantially increased suspended-sediment loads for the construction. Daily suspended-sediment loads at low flows, however, appear to have been increased during construction, and these increases resulted in the changes in streamflow-sediment relations indicated in table 9.

No significant changes in suspended-sediment transport were detected at station 272200 (table 9; fig. 9). Deposition of sediment in Waimaluhia Reservoir upstream of the station reduces suspended-sediment loads at station 272200, and any increase in sediment mobilization resulting from highway or golf-course construction might not be detected at the station. Bathymetric surveys indicated that volume of the reservoir decreased by 5.9 acre-ft because of sediment deposition from 1983 to 1988 (Wong and Hill, 1992). Work is currently in progress to determine rates of sediment deposition in the reservoir since 1988.

Pre-construction and construction-period regression equations cannot be used to estimate construction effects on suspended-sediment loads because of limitations of the statistical techniques used. At all stations except station 270900, the range of streamflow data during construction exceeds the range before construction. Extrapolation beyond the range of data used to develop the regressions can lead to serious errors because sediment transport relations commonly change as streamflow increases (Nolan and others, 1986; Glysson, 1987). Also, the use of tobit regression in place of ordinary least squares regression means that residuals cannot be used to determine appropriate regression relations or bias-correction factors (Helsel and Hirsch, 1992). Instead, regional sediment-transport relations were used to estimate construction effects, as described later in the section "Regional comparison of suspended-sediment yields."

Suspended-Sediment Yields at Stream-Gaging Station 265600

Construction-period suspended-sediment loads at stream-gaging station 265600 were compared with pre-construction loads at stream-gaging station 270900 to determine whether construction-period loads at station 265600 were significantly different from pre-construction loads on the same days at nearby station 270900. Suspended-sediment loads were divided by drainage-basin areas to allow direct comparison of yields for the two stations. Differences between daily yields were tested for significance using the Wilcoxon signed-ranks test (Iman and Conover, 1983).

The average daily suspended-sediment yield at station 265600 was 2.01 t/mi^2 during the pre-construction period for station 270900. The average daily suspended-sediment yield at station 270900 during this pre-construction period was 1.40 t/mi^2. These averages were significantly different ($p<0.0001$). Construction-period suspended-sediment yields at station 265600 therefore were significantly higher than pre-construction yields on the same days at station 270900, indicating a significant effect of construction at station 265600. Golf course construction upstream of station 265600 probably increased sediment loads at this station and added to the apparent effects of highway construction. However, data are insufficient to quantify the effects of golf course construction or to determine the relative importance of highway or golf course construction on sediment loads at station 265600.

Evaluation of State Water-Quality Standards

The State of Hawaii Department of Health has established standards for total nonfilterable residue for streams in the State of Hawaii (State of Hawaii Department of Health, 1990). Separate standards were established for the dry season (May 1 through October 31) and the wet season (November 1 through April 30). The standards are as follows: for the dry season, geometric mean not to exceed 10 mg/L, concentrations not to exceed 30 mg/L for more than 10 percent of the time or 55 mg/L for more than 2 percent of the time; for the wet season, geometric mean not to exceed 20 mg/L, concentrations not to exceed 50 mg/L for more than 10 percent of the time or 80 mg/L for more than 2 percent of the time.

Total nonfilterable residue is similar to suspended-sediment concentration in that both are measures of the amount of suspended material present in a water sample. Total nonfilterable residue is determined for an aliquot of sample that may not be representative of the whole sample, especially if large quantities of sand are present. Sand settles quickly, and aliquots removed for total nonfilterable residue are likely to be either depleted or enriched in sand, depending on where the aliquot was collected in the sample bottle. Whole samples are used for suspended-sediment concentration analyses. For this reason, suspended-sediment concentration is generally a more accurate measure of suspended materials (Fishman and Friedman, 1989, p. 443).

During the H-3 highway study, 13 samples collected concurrently with suspended-sediment samples were analyzed for total nonfilterable residue. Suspended-sediment concentrations for these pairs of samples ranged from 6 to 659 mg/L. Suspended-sediment concentrations were higher than total nonfilterable residue for each sample pair. The average difference was 35 percent of the suspended-sediment concentration. Suspended-sediment concentrations therefore tend to overestimate total nonfilterable residue concentrations by about 35 percent, and these two measures of suspended material cannot be considered equivalent. However, because both suspended-sediment concentration and total nonfilterable residue are measures of suspended material in streams, and because suspended-sediment concentration data are available on a daily basis and total nonfilterable residue data are not, suspended-sediment concentrations were substituted for total nonfilterable residue concentrations in the analysis of water-quality standards compliance. Although results cannot be used directly to determine whether highway construction caused exceedance of water-quality standards, they provide a general assessment of standards compliance before and during construction.

Daily values of suspended-sediment concentration, separated into wet and dry season data, were used to assess compliance with State water-quality standards. The geometric mean was computed as the antilog of the arithmetic mean of log-transformed data. The time percentages that daily concentrations were exceeded were determined by sorting and ranking the concentration data for each year, and dividing the ranks by the number of days in the season (wet or dry) for that year to get a cumulative relative frequency. These frequencies were subtracted from 1.00 to obtain the percentage of time each concentration was equalled or exceeded. Daily values of concentration reported as 0 were replaced with estimates derived from log-probit regression (Helsel and Hirsch, 1992) to permit computation of the geometric mean.

State water-quality standards were exceeded at all H-3 stations during most but not all years of the construction periods (table 10), on the basis of the analysis described above. Standards also were exceeded in 2 years of the pre-construction periods at stations 270900 and 275000. In many cases, standards were exceeded by much more than the 35 percent error that could be attributed to the substitution of suspended-sediment concentrations for total nonfilterable residue concentrations.

Estimated Magnitude of Highway-Construction Effects on Suspended-Sediment Loads

Highway construction can accelerate erosion and suspended-sediment transport through disturbance of soil and vegetation cover, channel realignments, and decreased hillslope stability as a result of cutting and filling. Previous studies of highway construction in

Table 10. Evaluation of State water-quality standards for selected stream-gaging stations, Oahu, Hawaii

[Suspended-sediment concentrations were used in place of total nonfilterable residue, and results therefore can only indicate possible exceedance of the standards; * indicates possible exceedance of standard; > indicates that the computed percentage of time was greater than the value indicated by less than 0.5 percent; station numbers are abbreviated, complete numbers are preceded by 16]

Water year	Season	Geometric mean[1] (mg/L)	Concentration (mg/L) exceeded: 10 percent of time	Concentration (mg/L) exceeded: 2 percent of time	Percentage of time: 30 mg/L (dry) 50 mg/L (wet) exceeded	Percentage of time: 55 mg/L (dry) 80 mg/L (wet) exceeded
			Station 226200			
1983[2]	dry	1	6	16	0	0
	wet	--	0	0	0	0
1984	dry	0	2	10	0	0
	wet	1	4	16	0	0
1985	dry	1	4	20	0	0
	wet	2	8	50	0	0
1986	dry	2	7	38	0	0
	wet	1	6	28	0	0
1987	dry	2	9	37	0	0
	wet	2	10	39	0	0
1988	dry	3	37*	307*	11	8
	wet	7	59*	309*	11	8
1989	dry	12*	64*	523*	14	10
	wet	44*	668*	1,336*	38	35
1990	dry	5	26	169*	0	6
	wet	5	19	171*	0	3
1991	dry	10	44*	180*	13	8
	wet	9	111*	430*	15	11
			Station 265600			
1983[3]	dry	13*	45*	115*	22	5
	wet	9	21	43	0	0
1984	dry	11	24	51	0	0
	wet	9	34	91*	0	3
1985	dry	13*	34*	99*	12	6
	wet	10	32	126*	0	3
1986	dry	10	19	106*	0	4
	wet	9	11	72	0	0
1987	dry	14*	28	77*	0	7
	wet	18	26	118*	0	5
1988	dry	9*	26	103*	0	5
	wet	10*	52*	207*	>10	7
1989	dry	22*	42*	74*	14	6
	wet	30*	95*	257*	14	12
1990	dry	13*	34*	110*	13	7
	wet	18	71*	419*	12	9
1991	dry	7	20	39	0	0
	wet	16	61*	133*	14	5
			Station 270900			
1984[4]	dry	4	8	11	0	0
	wet	6	14	44	0	0
1985	dry	4	5	7	0	0
	wet	5	11	46	0	0
1986	dry	6	8	48	0	0
	wet	6	8	27	0	0
1987	dry	5	5	64*	0	>2
	wet	5	6	194*	0	3
1988	dry	4	5	7	0	0

Table 10. Evaluation of State water-quality standards for selected stream-gaging stations, Oahu, Hawaii--Continued

Water year	Season	Geometric mean[1] (mg/L)	Concentration (mg/L) exceeded: 10 percent of time	Concentration (mg/L) exceeded: 2 percent of time	Percentage of time: 30 mg/L (dry) 50 mg/L (wet) exceeded	Percentage of time: 55 mg/L (dry) 80 mg/L (wet) exceeded
			Station 270900--Continued			
	wet	5	22	167*	0	5
1989	dry	5	7	80*	0	>2
	wet	10	50	222*	0	7
1990	dry	7	10	50	0	0
	wet	7	20	46	0	0
1991	dry	20*	43*	175*	22	6
	wet	19	88*	250*	20	12
			Station 272200			
1983	dry	6	10	17	0	0
	wet	8	15	31	0	0
1984	dry	10	23	33	0	0
	wet	10	18	64	0	0
1985	dry	11*	27	60*	0	>2
	wet	16	29	53	0	0
1986	dry	8	14	40	0	0
	wet	8	12	15	0	0
1987	dry	7	16	109*	0	5
	wet	7	13	39	0	0
1988	dry	3	7	19	0	0
	wet	8	42	197*	0	5
1989	dry	21*	58*	130*	31	11
	wet	19	35	189*	0	6
1990	dry	14*	141*	237*	21	15
	wet	12	43	115*	0	3
1991	dry	8	18	33	0	0
	wet	17	45	139*	0	4
			Station 275000			
1984[5]	dry	3	5	12	0	0
	wet	6	14	21	0	0
1985	dry	--	--	--	--	--
	wet	--	--	--	--	--
1986	dry	--	--	--	--	--
	wet	--	--	--	--	--
1987[6]	dry	7	18	120*	0	3
	wet	--	--	--	--	--
1988	dry	3	8	21	0	0
	wet	9	61*	257*	11	8
1989	dry	9	19	160*	0	3
	wet	15	89*	637*	13	10
1990	dry	6	16	153*	0	4
	wet	10	68*	595*	11	8
1991	dry	2	8	74*	0	>2
	wet	6	99*	687*	13	11

[1] computed using log-probability regression to estimate values for data reported as zero
[2] data for water year 1983 from February 1 through September 30; all wet season concentrations were zero, and the geometric mean could not be computed
[3] data for water year 1983 from February 1 through September 30
[4] data for water year 1984 from April 1 through September 30
[5] data for water year 1984 from December 1 through September 30
[6] data for water year 1987 from July 20 through September 30; no wet season data

other areas have shown that construction can contribute as much as five times the amount of sediment contributed from all other sources (table 2).

Regional Comparison of Suspended-Sediment Yields

Annual suspended-sediment yields reported for other areas of Oahu (Jones and others, 1971; Doty and others, 1981; Shade, 1984) were used to extend the range of pre-construction data at H-3 study stream-gaging stations in order to estimate the effects of construction. Annual suspended-sediment yields during construction at stations 226200, 265600, and 275000 were higher than pre-construction yields and yields from nearby drainage basins unaffected by highway construction for comparable values of annual water yield (streamflow per unit area); (fig. 10). Yields during construction at station 270900, however, were within the range of yields for drainage basins unaffected by highway construction. Suspended-sediment yields at station 272200 cannot be compared with yields at other stations because the reservoir upstream of the station traps sediment and reduces the yield at the station.

Annual water yields (streamflow per unit area) and suspended-sediment yields for drainage basins in the leeward Koolau Range were combined with pre-construction data for station 226200 (fig. 10) to compute a regression equation relating suspended-sediment yield to water yield under pre-construction conditions for leeward Koolau drainage basins. This regression equation was used to estimate the suspended-sediment yields expected at station 226200 during the construction period without the effects of highway construction. Transformation to common logarithms was used to obtain a more linear relation, which was expressed:

$$\log Sy = -2.91 + (1.96 \times \log Qy), \qquad (5)$$

where Sy represented annual suspended-sediment yield and Qy represented annual water yield. A total of 18 annual suspended-sediment yields was used to compute the regression, which had a coefficient of determination of 86 percent and a standard error of 0.22 log units.

The same procedure was used for stations 265600, 270900, and 275000 using pre-construction data from these stations and for windward stations used in previous studies (fig. 10), except that log-transformation was not necessary. The regression equation, computed with 14 measured suspended-sediment yields, was expressed as:

$$Sy = 30 + (0.529 \times Qy). \qquad (6)$$

The coefficient of determination for equation 6 was 56 percent, and the standard error was 336 t/mi^2. For both the leeward and windward regressions, yields from drainage basins under mixed use were combined with yields from undisturbed drainage basins, since land use other than highway construction was not clearly a factor affecting yields.

Annual suspended-sediment yields expected in the absence of construction effects were estimated by applying regression equations 5 and 6 to construction-period annual water yields. For station 226200, a bias-correction factor of 1.15 was applied to correct for retransformation error (Duan, 1983). These estimates were subtracted from observed annual suspended-sediment yields. The resulting differences represent the increased or decreased yields attributable to construction. Sums of the annual differences were divided by sums of observed annual construction-period yields and multiplied by 100 to obtain the percentages of the construction-period suspended-sediment yields resulting from highway construction.

Sums of annual differences ranged from -920 t/mi^2, equivalent to -71 percent of the observed suspended-sediment yield, at station 270900, to 6,260 t/mi^2, or 76 percent of the observed yield, at station 275000 (table 11). The increased yield at station 226200 was equivalent to 59 percent of the observed yield, and the increased yield at station 265600 was equivalent to 56 percent of the observed yield (table 11). The suspended-sediment loads resulting from construction activities therefore ranged from 56 to 76 percent of the measured loads at the three stations where significant increases in suspended-sediment loads were detected.

The negative difference for station 270900 (table 11) indicates that suspended-sediment yields during construction would have been higher under pre-construction conditions than under construction conditions. Before construction, most of the drainage basin upstream of station 270900 was under cultivation for bananas. Although agricultural practices generally increase sediment yields (El-Swaify and others, 1982), no studies have documented sediment yields from banana plantations in Hawaii. Cultivation of plantains, which are similar to bananas, can result in soil losses as high as 70 percent of losses for bare soil (El-Swaify and others, 1982); such losses would be much higher than soil losses under natural vegetation. Pre-construction

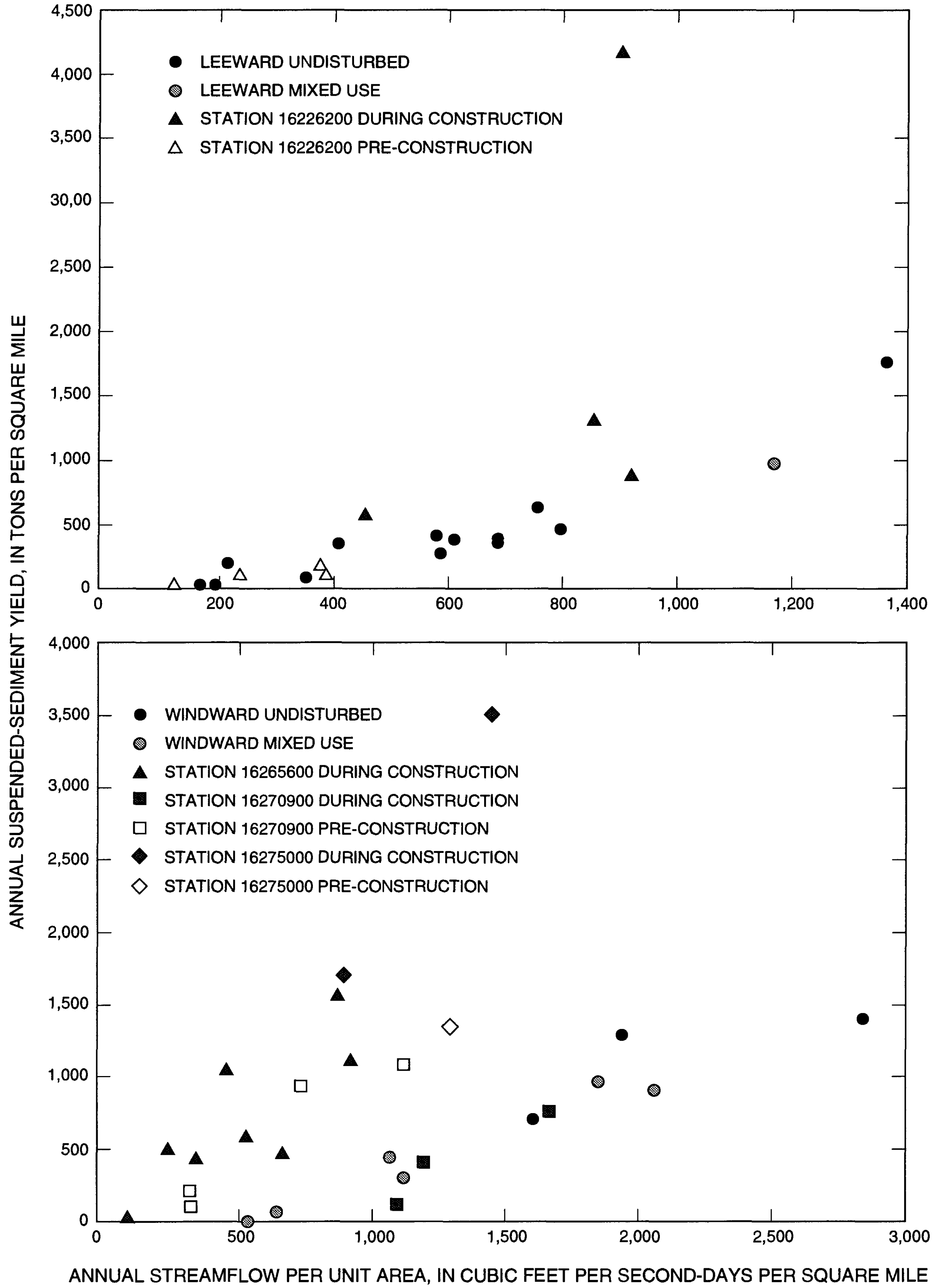

Figure 10. Annual streamflow and suspended-sediment yields for leeward and windward areas, Oahu, Hawaii.

Table 11. Observed and estimated annual suspended-sediment yields at selected stream-gaging stations during H-3 highway construction, Oahu, Hawaii

[Estimated yields were computed from regression equations relating annual suspended-sediment yields to annual streamflow per unit area; data used for station 226200 were log-transformed and a bias-correction factor of 1.15 was applied to estimated yields; data for all other stations were not log-transformed; tons/mi^2, tons per square mile; differences were computed as observed yield less estimated yield, and are reported in tons per square mile; percent differences are differences divided by observed yields and multiplied by 100; data used in regressions includes pre-construction data from this study and data from Jones and others (1971), Doty and others (1981), and Shade (1984); station numbers are abbreviated, complete numbers are preceded by 16]

Station	Suspended-sediment yields (tons/mi^2)		Difference (tons/mi^2)	Difference (percent)
	Observed	Estimated		
226200	6,880	2,840	4,040	59
265600	5,660	2,500	3,160	56
270900	1,290	2,210	–920	–71
275000	8,280	2,020	6,260	76

suspended-sediment yields at station 270900 appear to be higher than yields for other windward drainage basins under mixed use. The reduction in the area under cultivation during highway construction may have led to a reduction in sediment yield. Installation of erosion-control measures during construction may have also contributed to decreased soil losses.

Exceedance of State Water-Quality Standards

The exceedance of standards during the study period coincided in most cases with H-3 construction and with high rainfall; however, standards were not exceeded in every year of construction at stream-gaging stations 270900 and 272200 and standards were exceeded in 2 years before construction at stations 270900 and 275000 (table 10). Standards were also exceeded in 6 of 9 construction years at station 272200, although the analysis of covariance detected no significant effects of construction. Construction of the H-3 was probably a factor affecting exceedance of the standards, but other land uses as well as variations in rainfall probably were involved.

State water-quality standards (State of Hawaii Department of Health, 1990) are designed to minimize the amount of time that ambient suspended-sediment concentrations exceed threshold concentrations. No standards exist for suspended-sediment loads, that is, for the total amount of sediment transported by streams. A stream with occasional high loads could be in compliance with the standards, whereas a stream with persistent moderate loads could exceed the standards while transporting a lower suspended-sediment load. Fluvial sediment transport can be highly episodic, with most of the annual load being transported in just a few days (Nolan and others, 1987; Nolan and Hill, 1989). Compliance with the present State water-quality standards therefore does not necessarily indicate that sediment loads are low (Doty and others, 1981).

The standards are the same for wet years and dry years. Because of the interrelations between rainfall, streamflow, and sediment transport, standards will be exceeded more often during wet years than in dry years.

Comparison With Highway Construction Effects in Other Areas

The estimates of the percentage of suspended-sediment loads resulting from highway construction in this study range from 56 to 76 percent at the three stream-gaging stations where increases in suspended-sediment loads during construction were found to be significant (table 11). Previous studies in other areas found that 29 to 85 percent of the sediment loads were attributable to construction activities. Effects of H-3 highway construction on suspended-sediment loads at stations 226200, 265600, and 275000 appear to be comparable to effects of highway construction elsewhere. The decrease in suspended-sediment yield during highway construction period at station 270900 is unusual in view of results of previous studies and probably resulted from reduced agricultural activity and increased erosion control during highway construction.

CONCLUSIONS

Construction of the H-3 highway coincided with high rainfall. Annual streamflow and suspended-sediment loads increased during construction, partly in response to increased rainfall and partly in response to effects of highway construction and other land uses.

Low flows changed significantly during construction at two stream-gaging stations. Low flows increased 117 percent at station 270900 and decreased 28 percent at station 272200. Changes in low flows were probably the result of changes in ground-water withdrawal rates and highway construction.

No significant changes in high flows were detected. The relatively small areas affected by construction probably account for the lack of any significant construction effects on high flows.

Data were insufficient to determine changes in streamflow at station 265600. Comparison of streamflow data at this station under construction conditions with data at station 270900 under pre-construction conditions indicates that streamflows at station 265600 were significantly lower. This difference was probably caused by differences in the hydrogeology of the two drainage basins rather than by construction. Ground-water withdrawals from wells upstream of station 265600 may have decreased low flows slightly.

Suspended-sediment loads increased significantly during construction at stream-gaging stations 226200, 265600, and 275000. Highway construction contributed between 56 and 76 percent of the suspended-sediment loads measured at these stations during construction. Loads did not change significantly at station 272200, which is downstream of a reservoir that traps sediment from construction areas. Loads decreased during construction at station 270900, which is downstream of a drainage basin heavily used for agriculture before construction. The decreased loads at this station may have been because of decreased agricultural activity and erosion-control measures installed for highway construction. Effects of H-3 highway construction on suspended-sediment loads were generally similar to effects of highway construction in other areas. State water-quality standards for suspended sediment were frequently exceeded during construction. Standards were exceeded occasionally before construction.

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