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Streamflow and Suspended-Sediment Loads Before, During, and After H-3 Highway Construction, North Halawa, Haiku, South Fork Kapunahala, and Kamooalii Drainage Basins, Oahu, Hawaii,1983–99

U.S. Department of the Interior
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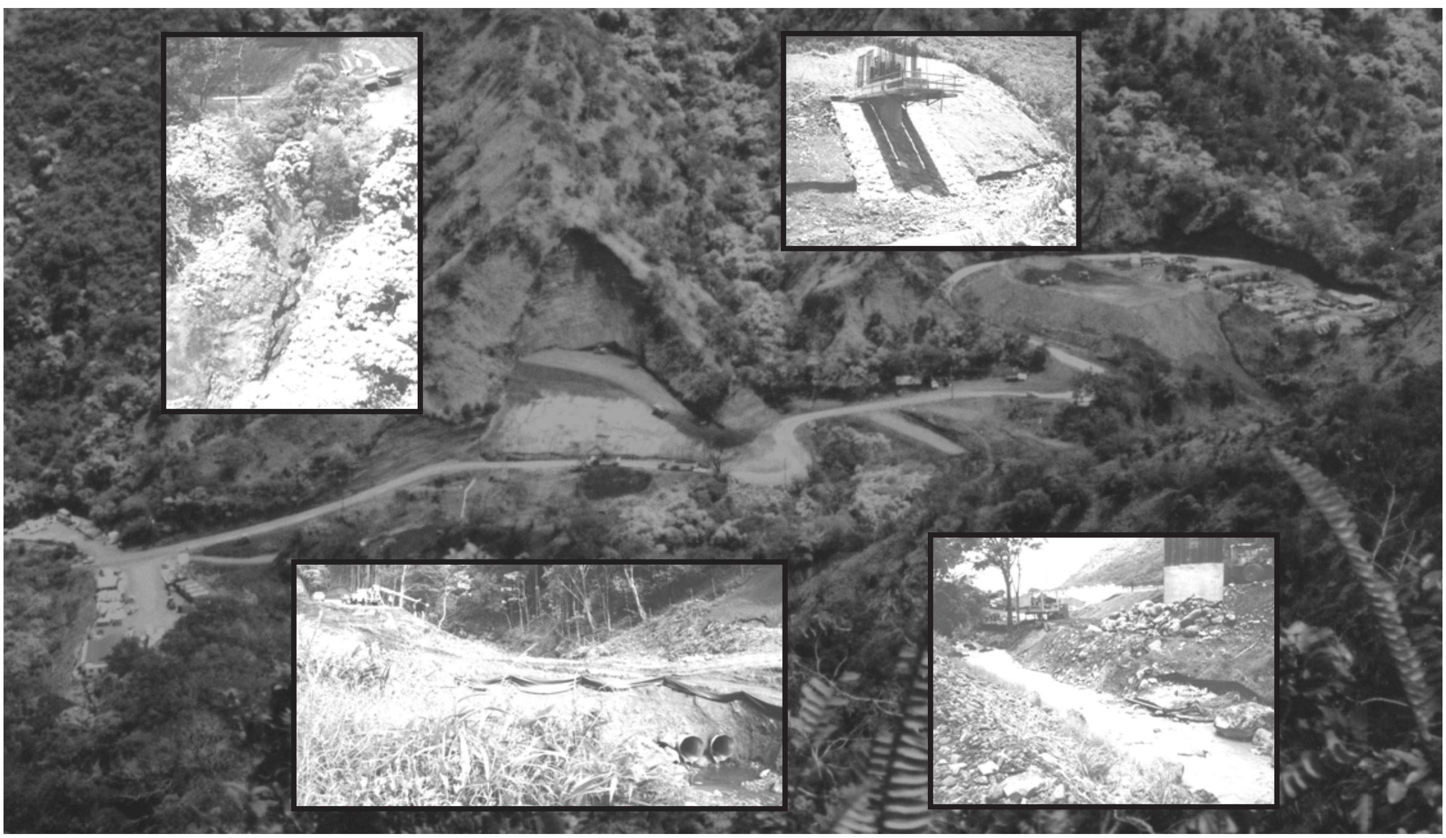
Water-Resources Investigations Report 02-4005



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

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GLOSSARY

Drainage area - An area from which surface runoff or streamflow is carried away by a single drainage system. Also called drainage basin.

Regression equation - An equation derived by methods of regression. A mathematical relation between a response variable and one or more explanatory variables.

Residuals or regression error - The difference between the observed and computed values derived from a regression equation.

Sediment - Solid material that originates mostly from disintegrated rocks and is transported by, suspended in, or deposited from water; it includes chemical and biochemical precipitates and decomposed organic material such as humus.

Streamflow or water discharge - The rate of water flowing past a section of stream channel. Expressed as volume per unit of time, such as cubic feet per second.

Suspended-sediment - The sediment that at any given time is maintained in suspension by the upward components of turbulent currents or that exists in suspension as a colloid.

Suspended-sediment discharge or load - The rate at which sediment passes a section of a stream or is the quantity of sediment, as measured by dry weight, or by volume, that is discharged in a given time. Usually expressed as tons per day.

Suspended-sediment yield - The suspended-sediment discharge or load per unit of drainage area. Expressed as volume per unit area, such as tons per square mile.

Water year - The 12–month period, October 1 through September 30. The water year is designated by the year in which it ends. Thus, the water year ending September 30, 1999, is called the “1999 water year.”

Streamflow and Suspended-Sediment Loads Before, During, and After H-3 Highway Construction, North Halawa, Haiku, South Fork Kapunahala, and Kamooalii Drainage Basins, Oahu, Hawaii, 1983–99

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Abstract

A long-term study (1983–99) was conducted to determine the effects of the H-3 Highway construction on streamflow and suspended-sediment transport on Oahu, Hawaii. Data were collected at five streamflow-gaging stations before, during, and after construction and at two stream-gaging stations during and after construction. Drainage areas at the seven streamflow-gaging stations ranged from 0.40 to 4.01 mi^2 and highway construction affected from 4 to 15 percent of these areas. Analysis of covariance and regression techniques were used to assess changes in streamflow and suspended-sediment loads during and after construction, relative to before-construction conditions.

Streamflow at the seven streamflow-gaging stations was compared to streamflow at an index station unaffected by highway construction. Streamflow data were divided into low- and high-flow classes, and the two flow classes were analyzed separately. Additionally, instantaneous peak flows were analyzed at three streamflow-gaging stations. During construction, observed low flows significantly increased by 108 percent at Luluku Stream, a tributary to Kamooalii Stream, and decreased by 31 percent at Kamooalii Stream. After construction, low flows increased by 47 percent at North Halawa Stream near Honolulu compared to low flows during construction. Low flows at Luluku Stream increased by 99 percent after construction compared to before construction. Increased low flows were attributed to removal of vegetation for construction and the increase of impervious areas that reduced infiltration. Decreased low flows were attributed to increased ground-water withdrawals and construction activities.

High flows observed during highway construction compared to before construction increased significantly only at Haiku Stream (by 25 percent). Observed high flows after construction compared to during construction increased significantly only at Kamooalii Stream (by 34 percent). Observed high flows after construction compared to before construction increased by 58 percent only at Luluku Stream. All increases in observed high flows are attributed to increased runoff from land-use changes caused by the highway construction. Instantaneous peak flows increased significantly at Luluku Stream. Luluku Stream had significant increases in low and high flows both during and after construction.

Suspended-sediment loads changed significantly at six out of seven sediment-gaging stations during highway construction. Construction activities increased observed suspended-sediment yields by 222, 426, 60, and 148 percent at North Halawa Stream near Kaneohe, North Halawa Stream near Honolulu, Right Branch Kamooalii Stream, and Haiku Stream, respectively. At Luluku Stream, observed suspended-sediment yields were lower during construction than before construction by 62

percent. After construction, suspended-sediment loads also changed significantly at six out of seven stream-gaging stations. Observed after-construction yields increased at North Halawa Stream near Kaneohe, North Halawa Stream near Honolulu, and Right Branch Kamooalii Stream by 49, 205, and 36 percent, respectively, and decreased at Kamooalii Stream and South Fork Kapunahala Stream by 62 and 71 percent. The observed increases in yields are smaller after construction than during construction indicating that suspended-sediment loads are likely returning to before-construction levels.

The effects of H-3 Highway construction on suspended-sediment loads were generally similar to studies of the effects of highway construction in other areas of the United States where 50 to 85 percent of the sediment loads were attributed to construction activities. The percentages of the observed yields attributable to H-3 Highway construction are similar to the above percentages, ranging from 37 to 81 percent. Decreases in suspended-sediment loads due to highway construction are unique and have not been widely reported in the literature. Where decrease in suspended-sediment loads were determined, land use prior to construction was not pristine.

INTRODUCTION

The H-3 Highway is a major highway across the Koolau Range on the eastern part of the island of Oahu, Hawaii (fig. 1). Potential effects of construction, such as soil erosion and stream sedimentation, on streams along the route were an issue of public concern and construction began only after a lengthy environmental evaluation (U.S. Department of Transportation, Federal Highway Administration, and State of Hawaii Department of Transportation, 1987). In 1983, the U.S. Geological Survey, in cooperation with the State of Hawaii Department of Transportation and Federal Highway Administration, began a study to help assess the effects of the highway construction on streamflow and suspended-sediment transport in these streams.

Purpose and Scope

The purpose of the study was to compare data collected before, during, and after highway construction to determine if construction activities have affected streamflow and suspended-sediment transport. The purpose of this report is to identify and quantify effects of H-3 Highway construction on streamflow and suspended-sediment loads between 1983 and 1999, which included periods before, during, and after construction. Statistical methods used in this study follow those used by Hill (1996), who conducted a previous analysis using data collected from 1981 through 1991 covering before and during construction. This report extends the work by Hill (1996) through the end of data collection in 1999.

Rainfall, streamflow, and suspended-sediment data collected at a network of stream-gaging stations (figs. 1 and 2) were used to determine if streamflow and suspended-sediment loads changed significantly during and after construction. Changes due to construction were quantified by comparing data collected during construction to data collected before and after construction. Daily, monthly, and annual values of streamflow, suspended-sediment concentration and discharge, and suspended-sediment particle size analyses have been published in the annual water-resources data reports of the U.S. Geological Survey of which Hill and others (2000) is an example. Data from two gaging stations were not published in the annual data reports because the majority of the data were considered interpretive. These data are for station 16265600, water year 1996, suspended-sediment discharge and for station 16273950, water year 1997, streamflow and suspended-sediment discharge. Estimates and data for both these stations are presented at the end of the report in appendix 1 through 3. Additional streamflow and suspended-sediment data collected from 1981 were used at station 16272200 and additional peak flow data from 1971 were used at stations 16226000, 16270900, and 16275000. Additional streamflow data collected at station 16226000 in North Halawa Valley was used to help analyze streamflow data at another North Halawa Stream station, 16226200. Station numbers are used throughout the report to refer to locations of data collection and their corresponding drainage basins. Table 1 lists station numbers and their corresponding station names, drainage areas, locations, and periods of streamflow and suspended-sediment record.

Table 1. Locations and period of record at streamflow-gaging stations in and near the H-3 Highway study area, Oahu, Hawaii
[mi^2, square miles; horizontal datum for latitude and longitude coordinates is Old Hawaiian]

Station number	Station name	Drainage area (mi^2)	Latitude	Longitude	Period of streamflow record	Period of suspended-sediment record
16225800	North Halawa Stream near Kaneohe	1.64	21°24′33″	157°52′06″	Apr 1991 to Sept 1999	Apr 1991 to Sept 1999
16226000	North Halawa Stream near Aiea	3.45	21°23′46″	157°53′37″	[1]July 1953 to present	None
16226200	North Halawa Stream near Honolulu	4.01	21°23′04″	157°54′22″	Feb 1983 to present	Feb 1983 to Sept 1999
16229000	Kalihi Stream near Honolulu	2.61	21°22′00″	157°50′49″	[2]July 1914 to present	None
16265600	Right Branch Kamooalii Stream near Kaneohe	1.11	21°23′22″	157°47′44″	Feb 1983 to Sept 1997	Feb 1983 to Sept 1997
16270900	Luluku Stream at altitude 220 feet near Kaneohe	0.44	21°23′42″	157°48′44″	[3]Apr 1984 to June 1998	Apr 1984 to June 1998
16272200	Kamooalii Stream below Luluku Stream near Kaneohe	3.81	21°23′47″	157°48′23″	Nov 1976 to present	Nov 1976 to Sept 1998
16273950	South Fork Kapunahala Stream at Kaneohe	0.40	21°24′21″	157°48′31″	Oct 1987 to June 1998	Oct 1987 to June 1998
16275000	Haiku Stream near Heeia	0.97	21°24′46″	157°49′33″	[4]Oct 1982 to present	[5]July 1987 to Sept 1998

[1] Streamflow data were previously collected 1929–33
[2] Streamflow data were previously collected September 1913–April 1914
[3] Streamflow data were previously collected 1960–63 (low flows only), 1965–71, 1971–84 (annual maximum only)
[4] Streamflow data were previously collected 1914–19, 1939–77
[5] Suspended-sediment data were previously collected December 1983 to September 1984

H-3 Highway Construction

The H-3 Highway route traverses the drainage basins of North Halawa, Haiku, Kapunahala, and Kamooalii Streams (figs. 1 and 2). The H-3 Highway 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 Highway connects to a previously constructed section of highway leading from Kamehameha Highway to Kaneohe Marine Corps Base Hawaii. The completed H-3 Highway consists of both on-surface cut-and-fill and raised viaduct sections 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 Highway Administration and State of Hawaii Department of Transportation, 1987). Highway construction affected from 4 to 15 percent of the drainage basin areas upstream in the H-3 Highway study area.

Construction of the H-3 Highway proceeded in increments (table 2). Construction was at times halted by court actions, and the planned route was 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 were used throughout construction of the H-3 Highway to reduce sediment delivery from construction areas in all affected drainage basins. These measures included silt fence barriers installed on hillslopes and along channels, loose-rock check dams in channels, and hydro mulching and installation of plastic fabric netting on cut-and-fill slope faces. Streamflow in several channel reaches in upper portion of the North Halawa Valley was diverted into culverts, which were then buried, during construction to prevent sediment disturbed by construction from reaching the stream.

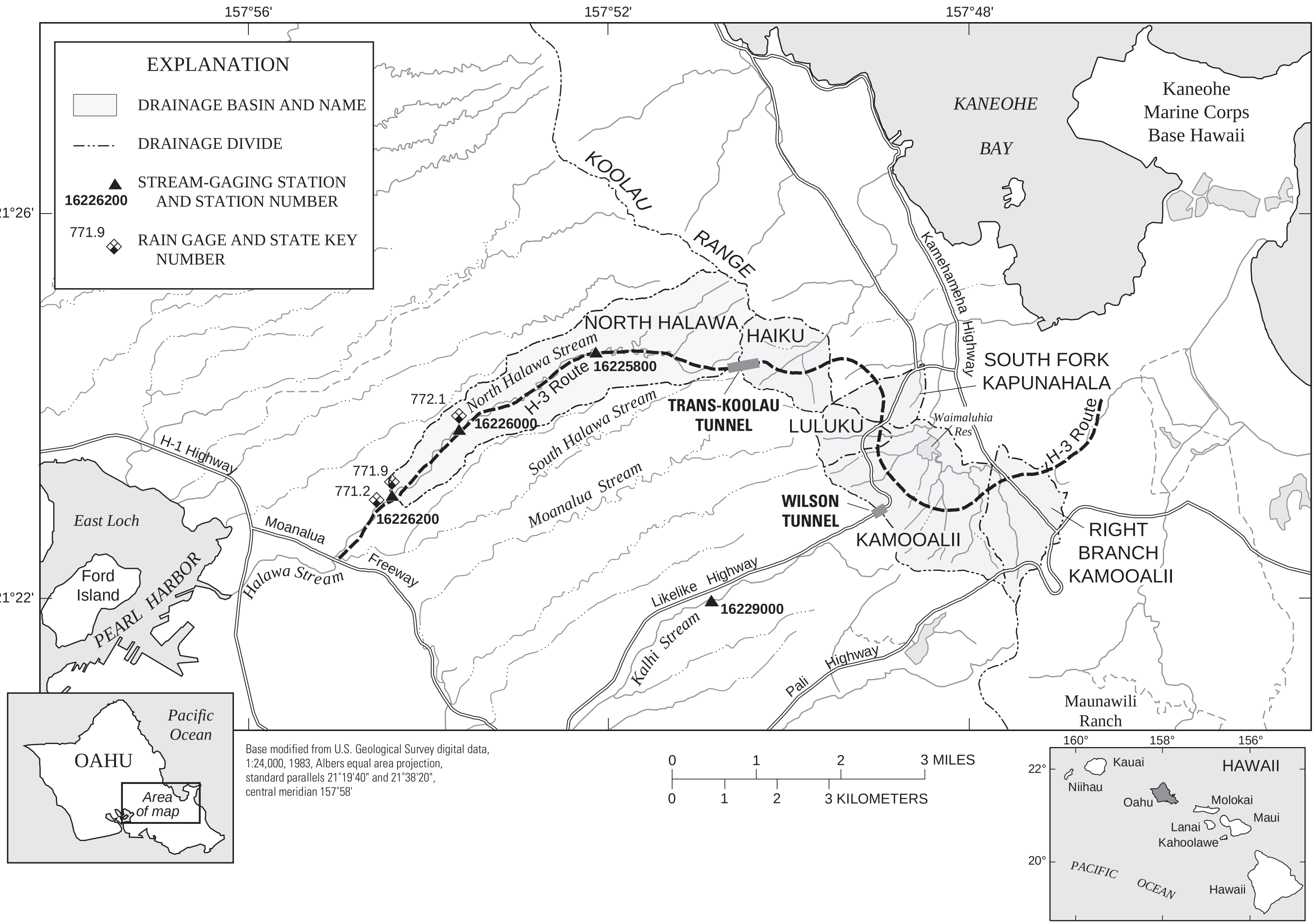

Figure 1. Selected stream-gaging and rain-gaging stations and drainage basins in and near the H-3 Highway study area, Oahu, Hawaii.

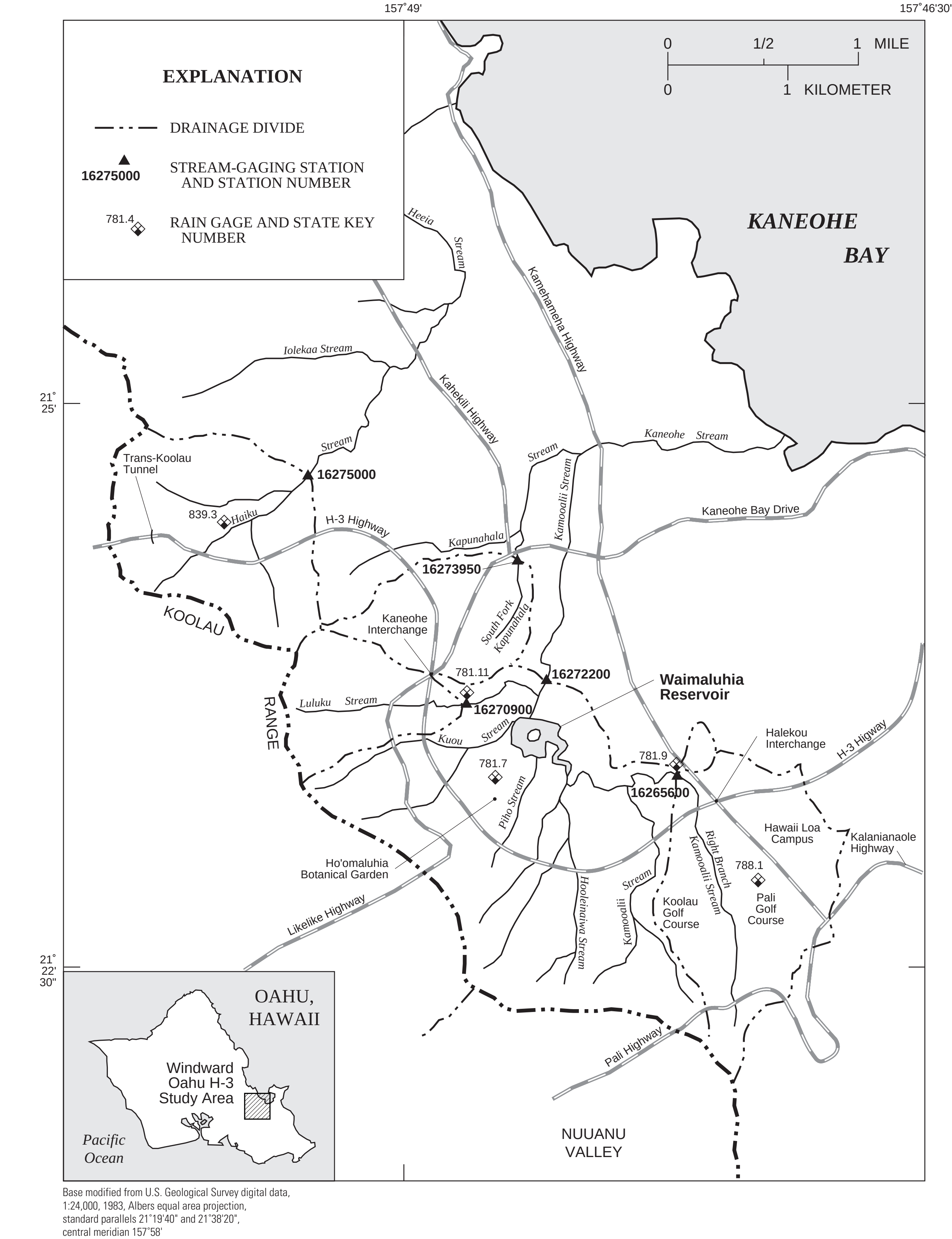

Figure 2. Selected stream-gaging and rain-gaging stations in the windward area of the H-3 Highway study area, Oahu, Hawaii.

Table 2. Chronology of highway construction activities within drainage basins of the H-3 Highway study area, 1983–99, Oahu, Hawaii
[Locations of streamflow-gaging stations are shown in figures 1–2; do., ditto. Start and end dates provided by the State of Hawaii, Department of Transportation, (written commun., 1999)]

Station	Drainage basin and highway construction activities	Start date	End date
16225800	**N. Halawa Stream**[1]		
	Trans-Koolau tunnel	03/19/91	02/07/98[2]
	N. Halawa viaduct	02/21/92	06/95
16226200	**N. Halawa Stream**[3]		
	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	02/07/98[2]
	N. Halawa viaduct	02/21/92	06/95
	N. Halawa Valley highway Unit I Phase 1A	04/11/94	09/95
	N. Halawa Valley highway Unit I Phase 1B	05/24/95	12/12/97
	N. Halawa Valley highway Unit II	08/01/94	12/12/97
16265600	**Right Branch Kamooalii Stream**		
	Halekou Interchange[4]	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
	Windward highway	06/19/89	06/92
16270900	**Luluku Stream**		
	Windward highway	06/19/89	06/92
	Kaneohe Interchange	01/19/93	12/22/95
16272200	**Kamooalii Stream**[5]		
	Windward highway	06/19/89	06/92
16273950	**S. Fork Kapunahala Stream**		
	Hospital Rock tunnel	03/06/89	05/92
	Kaneohe Interchange	01/19/93	12/22/95
16275000	**Haiku Stream**		
	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	05/13/93
	Trans-Koolau tunnel	10/01/90	02/07/98[2]

[1] Data collection did not start until April 1991
[2] This is the official completion date for all work on the tunnel, however for the Haiku Valley portion of the tunnel construction, all land disturbance work was completed by 11/94, so for the purpose of determining the post-construction dates, 11/94 will be used. In North Halawa Valley, channel and earthwork by the tunnel continued until 09/97, so 09/30/97 will be used for the purpose of determining the post-construction dates.
[3] Same construction activities and dates apply to station 16226000 except for N. Halawa Valley highway Unit I Phase 1A
[4] Work on Halekou Interchange interrupted multiple times by court injunctions
[5] Includes highway construction activities listed under stations 16265600 and 16270900, as these drainage basins drain into Kamooalii Stream

Study Area

The Koolau Range is the eroded remnant of the larger and younger of the two major shield volcanoes that formed the island of Oahu (Hunt, 1996). Much of the windward side of the original Koolau Volcano has been eroded, leaving a steep windward slope indented with short, broad, amphitheater-shaped valleys (Hinds, 1925). In contrast, the gentle leeward slope is deeply dissected by long, roughly linear valleys.

Geology of the study area consists primarily of Koolau Basalt that was extruded in numerous gently dipping thin (average of less than 10 ft) flows of lava that are intruded by near-vertical dense basaltic dikes near the crest of the present Koolau Range (Hunt, 1996). 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 near the study area is about 74°F and monthly averages range from 65°F to 84°F (Owenby and Ezell, 1992). Temperatures above 95°F and below 50°F are rare on Oahu (Blumenstock and Price, 1967). The distribution of rainfall is affected by the prevailing northeasterly trade winds and the topography of the island. Because of the Koolau Range, which has an altitude range of 2,000 to 3,000 ft above mean sea level, there is orographic lifting and cooling of marine air masses moving with the trade winds which 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, Honolulu Board of Water Supply, written commun., 1942; Mink, 1960). Rainfall varies seasonally, with most rainfall falling between November and April. Median annual precipitation ranges from 60 to 120 in. on the windward side of the study area, and from 40 to more than 120 in. on the leeward side (Division of Water and Land Development, 1982). Average annual pan evaporation is between 50 to 60 in. on the windward side and between 30 to 70 in. on the leeward side of the study drainage basins (Ekern and Chang, 1985).

The temporal and spatial distribution of streamflow in the study area is determined almost exclusively by geology and climate. Streams on the windward side respond rapidly to the direct runoff that takes place during heavy rainfall. 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 is known to flow between windward drainage basins. Rainfall infiltrating in one valley may emerge as streamflow in another (Hirashima, 1963; 1971; Takasaki and others, 1969). On the leeward side of the Koolau Range, dikes are uncommon (Takasaki and Mink, 1985). Most infiltrating rainfall in the North Halawa Valley percolates to the basal aquifer and does not maintain base flows in the streams located there (Izuka, 1992). Streamflow in North Halawa Stream is intermittent and is dependent primarily on direct runoff that occurs during heavy rainfall. Streamflow is supplemented by the discharge of small quantities of ground water from alluvial aquifers that extend recession streamflows from rainfall only to a minor extent (Izuka, 1992).

The dramatic topography of the study area has been attributed to chemical weathering (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 or piping (Stearns and Vaksvik, 1935). The most obvious process of physical erosion is mass wasting of shallow soil and saprolite (weathered bedrock) on steep hillslopes in areas of high rainfall (Stearns and Vaksvik, 1935; Wentworth, 1943; White, 1949; Scott and Street, 1976; Wilson and others, 1992). Processes observed during the period of this study included numerous debris flows in North Halawa Valley (Hill and others, 1998), plunge pool erosion in all streams in the study area, and ground-water sapping at stations 16265600 and 16275000.

Soils in the North Halawa drainage basin are classified as low permeability, very stony clays of the Kaena series (Foote and others, 1972). Soils in the Haiku, South Fork Kapunahala, and Kamooalii drainage basins are classified as Lokelaa with some Kaneohe and Hanalei series silty clays. These types of silty clays have moderate permeability and are highly erodible on steep slopes (Foote and others, 1972). Most of the mountainous areas in the study area are classified as rough mountainous land, rock land, or rock outcrop (Foote and others, 1972), and little information is available on the soils of these areas.

The study area is completely covered with one form or another of vegetation, except for several areas of urban development. Most of the native vegetation on the windward side of the Koolau Range has been replaced by cultivated crops, non-native plants, and residential and commercial developments. Vegetation in the North Halawa Valley is representative of undisturbed forest on the leeward side of the Koolau Range and includes both native and non-native species.

North Halawa.--The North Halawa drainage basin is on the leeward side of the crest of the Koolau Range. North Halawa Stream joins the South Halawa Stream downstream of stream-gaging station 16226200 (fig. 1) before flowing into the East Loch of Pearl Harbor. The drainage area upstream of station 16226200 is 4.01 mi^2 and altitudes range from 160 to 2,800 ft above mean sea level. The stream gradient of North Halawa Stream is 0.077 ft/ft. The lower valley of North Halawa is deeply incised, with only a few small ephemeral tributaries. The stream 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 part of the drainage basin, channels are cut into bedrock and include several waterfalls. The stream is more than 100 ft above the freshwater-lens water table throughout the valley (Izuka, 1992), and flow in the main channel is intermittent in most years.

The H-3 Highway constitutes about 4 percent of the drainage area upstream of station 16226200. Before highway construction began in November 1987, this drainage basin was undeveloped but the lower valley was used for agriculture from 1850 to 1947 (Spear, 1990). A major water source, the Halawa Shaft, built by the Honolulu Board of Water Supply in 1940 to collect ground water from the freshwater lens is located 200 ft downstream from station 16226200. Pumpage from the Halawa Shaft does not affect streamflow at station 16226200 (Izuka, 1992). There are no streamflow diversions in the drainage basin except for the temporary channel diversions that were related to highway construction. The temporary diversions did not transfer surface water out of the drainage basin. Rainfall, streamflow, and suspended-sediment data collection at station 16226200 began in February 1983. Suspended-sediment data collection ended in September 1999. Rainfall and streamflow data have been continuously collected at station 16226000 (fig. 1), which is located 1.3 mi upstream of 16226200, since 1953. Peak flow data from 16226000 was used to determine if the highway had an effect on peak flows due to the long period of annual peaks at station 16226000. No streamflow data analysis was done on streamflow data collected at station 16226000 because mean daily streamflow data between 1622600 and 16226200 from February 1983 to September 1999 is highly correlated (linear correlation coefficient of 0.99) so results from station 16226200 data should be representative of station 16226000. No suspended-sediment data were collected at 16226000.

Data collection at station 16225800 (fig. 1) began in April 1991 and ended in September 1999. This station was established during the period of highway construction to help differentiate the suspended-sediment contributions of the upper North Halawa Valley, where construction was all viaduct, and the lower valley, where construction included both viaduct and cut-and-fill. The drainage area upstream of station 16225800 is 1.64 mi^2 and altitudes range from of 646 to 2,800 ft above mean sea level. The stream gradient upstream of this station is 0.151 ft/ft, substantially steeper then the stream gradient upstream of station 16226200 which is 0.077 ft/ft.

During the period of highway construction about 3,600 ft of stream channel was lined with concrete and boulders upstream of station 16225800 and about 2,000 ft of channel was lined downstream of station 16225800 but upstream of station 16226200 (Richard Dahilig, Parsons Brinckerhoff-Hirota Associates, written commun., 1999). The 3,600 ft of lined channel is about 43 percent of the channel length from the Trans-Koolau tunnel to station 16225800. The 2,000 ft of lined channel between stations 16225800 and 16226200 represents about 10 percent of the channel length between the two stations. The total 5,600 ft of lined channel represents about 20 percent of the channel length from the Trans-Koolau tunnel to station 16226200.

Large amounts of material were removed and deposited in the valley during various phases of the construction. Construction of the access road, exploratory tunnel and Trans-Koolau tunnel (table 5) removed

530,000,000 cubic yards and filled 95,400,000 cubic yards (Q.D. Truong, Parsons Brinckerhoff, Quade, and Douglas, Inc., written commun., 1993). During construction of the North Halawa viaduct and Highway units I and II (table 2) about 350,000 cubic yards of material was excavated and 59,800 cubic yards filled upstream of station 16225800 and about 578,000 cubic yards was cut and 286,000 cubic yards was filled downstream of station 16225800 but upstream of station 16226200 (Richard Dahilig, Parsons Brinckerhoff-Hirota Associates, written commun., 1999). Excavated material not used as construction fill was deposited at disposal sites in the valley.

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). The drainage area upstream of stream-gaging station 16275000 is 0.97 mi^2, and altitudes range from 272 to 2,500 ft. The stream gradient is 0.390 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. Perennial streamflow begins at about an altitude of 500 ft and continues downstream past station 16275000 (Izuka and others, 1993). Haiku Stream joins Iolekaa Stream downstream of station 16275000 to form Heeia Stream, which flows into Kaneohe Bay (fig. 2).

Almost all of the drainage basin upstream of station 16275000 was part of a U.S. Coast Guard navigational facility which was operated from 1944 to September 30, 1997. A municipal well and water development tunnel are located upstream of station 16275000. 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 1988 (table 2). The portion of the H-3 Highway located within the Haiku drainage basin was constructed entirely as a viaduct, and covers about 3 percent of the drainage area upstream from station 16275000. Construction activities in the basin included excavation of about 256,000 cubic yards of material and fill of about 92,500 cubic yards (Emilio Barroga Jr., State of Hawaii, Department of Transportation, written commun., 2000).

Streamflow data were collected before this study at station 16275000 from 1914 through 1919 and from 1939 through 1977. Streamflow data collection for the H-3 Highway study began in October 1982, and suspended-sediment data were collected from December 1983 through September 1984 and from July 1987 through September 1998.

South Fork Kapunahala.--The South Fork Kapunahala drainage basin lies to the southeast of the Haiku drainage basin (fig. 2). The drainage area upstream from station 16273950 is of 0.40 mi^2, and altitudes range from 111 to 2,800 ft above mean sea level. The stream gradient is 0.394 ft/ft. The headwaters of this small basin start in the steep cliffs of the Koolau Range and flow is perennial downstream from about the 200 ft elevation. The drainage basin consists of residential and agricultural lands. The stream channel consists mostly of boulders, cobbles, and gravel. H-3 Highway construction began in March 1989 in the drainage basin (see table 5), with the construction activities occurring in the upper basin near the 400 ft elevation and in the lower basin starting in January 1993. The H-3 Highway covers about 15 percent of the drainage area upstream of station 16273950 and not 3 percent as previously published (Hill 1996; Wong and Young, 2001). During construction about 779,000 cubic yards of material were removed and 771,000 cubic yards were filled. (Emilio Barroga Jr., State of Hawaii, Department of Transportation, written commun., 2000.) Streamflow and suspended-sediment data were collected from October 1987 to June 1998.

Kamooalii.--The Kamooalii drainage area upstream of stream-gaging station 16272200 is 3.81 mi^2, and altitudes range from 116 to 2,820 ft above mean sea level (fig. 2). The Kamooalii drainage basin includes the 1.11 mi^2 Right Branch Kamooalii drainage basin upstream of stream-gaging station 16265600 and the 0.44 mi^2 Luluku drainage basin upstream of stream-gaging station 16270900. Streamflow is perennial at all three stations. Kamooalii Stream joins Kapunahala Stream downstream of station 16272200 to form Kaneohe Stream, which flows into Kaneohe Bay. Waimaluhia Reservoir, a 26-acre flood-control reservoir, was constructed between 1976 to 1981 upstream of the confluence of Luluku and Kamooalii Streams. Streamflow at station 16272200 includes water flowing through Waimaluhia Reservoir and water from Luluku Stream that does not pass through the reservoir. The stream gradient upstream of station 16272200 is 0.094 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 the Waimaluhia Reservoir is a public park operated by the City and County of Honolulu (fig. 2). Below the Botanical Garden, most of the drainage basin has been developed for residential use. Upstream of the Botanical Garden to the east and southeast is the Pali Golf Course built in 1957, the Koolau Golf Course built between 1989 and 1991, and the Hawaii Loa Campus of Hawaii Pacific University (fig. 2). The remaining land area in the Kamooalii drainage basin is banana plantations or undeveloped land. Parts of both Likelike and Pali Highways cross the drainage basin near the Koolau Range (fig. 2).

Several municipal wells and a water development tunnel 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 that are used for golf course irrigation were drilled upstream from station 16265600 during the construction period. Average yearly pumpage from the municipal wells and tunnel from 1983 to 1999 was about 3 to 4 Mgal/d (data from Honolulu Board of Water Supply annual reports, 1981–99). Average yearly pumpage from 1990 to 1997 from the golf course wells was about 0.15 Mgal/d (computed from data provided by Neal Fujii, Commission on Water Resource Management, Department of Land and Natural Resources, State of Hawaii, written commun., 2000). Water is sometimes pumped from Luluku Stream upstream from station 16270900 to irrigate banana plantations.

Highway construction in the Kamooalii drainage basin began in 1983 (table 2). The H-3 Highway constitutes about 4 percent of the drainage area upstream from station 16272200. The area affected by the H-3 Highway includes about 5 percent, not 11 percent as previously published (Hill, 1996; Wong and Young, 2001), of the drainage area upstream from station 16270900 and about 5 percent of the drainage area upstream from station 16265600. A total of about 800,000 cubic yards of material was excavated and 700,000 cubic yards filled during construction in the Kamooalii drainage basin (Emilio Barroga Jr., State of Hawaii, Department of Transportation, written commun., 2000).

Streamflow and suspended-sediment data collection at station 16272200 began in 1976 and suspended-sediment data collection ended in September 1998. Data from October 1980, after dam closure for the Waimaluhia Reservoir, through September 1998 are used in this report. Streamflow and suspended-sediment data collection at station 16265600 started in February 1983 and ended in September 1997. At station 16270900, streamflow and suspended-sediment data were collected from April 1984 to June 1998. Streamflow data previously were collected at station 16270900 from 1960–63 (low flow only), 1965–71, and 1971–84 (annual maximum only).

Streamflow index station.--Streamflow data from gaging station 16229000, Kalihi Stream, was used an index or control for the statistical analyses described below. The Kalihi drainage basin is on the leeward side of the Koolau Range directly to the southwest of the Kamooalii drainage basin (fig. 1). The Kalihi drainage area upstream of station 16229000 is 2.61 mi^2, and altitudes range from 116 to 2,700 ft above mean sea level. Land use in the Kalihi drainage basin is about 1 percent residential near gaging station 16229000 and the Likelike Highway and Wilson Tunnel, built in the 1950s, occupies about 1 percent of the drainage area along the length of the Kalihi Valley (fig. 1). The remaining area is entirely covered with native and non-native vegetation. Streamflow at station 16229000 was unaffected by H-3 Highway construction, diversions, or any major change in land use. Water was withdrawn from tunnels until March 1989 and an aerator well since March 1989 upstream of the station, but these withdrawals were small, average yearly pumpage was 0.10 Mgal/d from 1981–99 (data from Honolulu Board of Water Supply annual reports, 1981–99) in comparison to streamflow and were nearly constant during the study period (fig. 3).

Previous Studies

Hill (1996) discussed the construction effects of the H-3 Highway up to 1991 on the streamflow and suspended-sediment loads at stations 16226200, 16265600, 16270900, 16272200, and 16272200. Hill (1996) concluded that low flows increased at station 16270900 and decreased at station 16272200 during construction, and that suspended-sediment loads increased at station 16226200, 16265600, and 16275000, did not change at station 16272200, and decreased at station 16270900 as a result of highway construction.

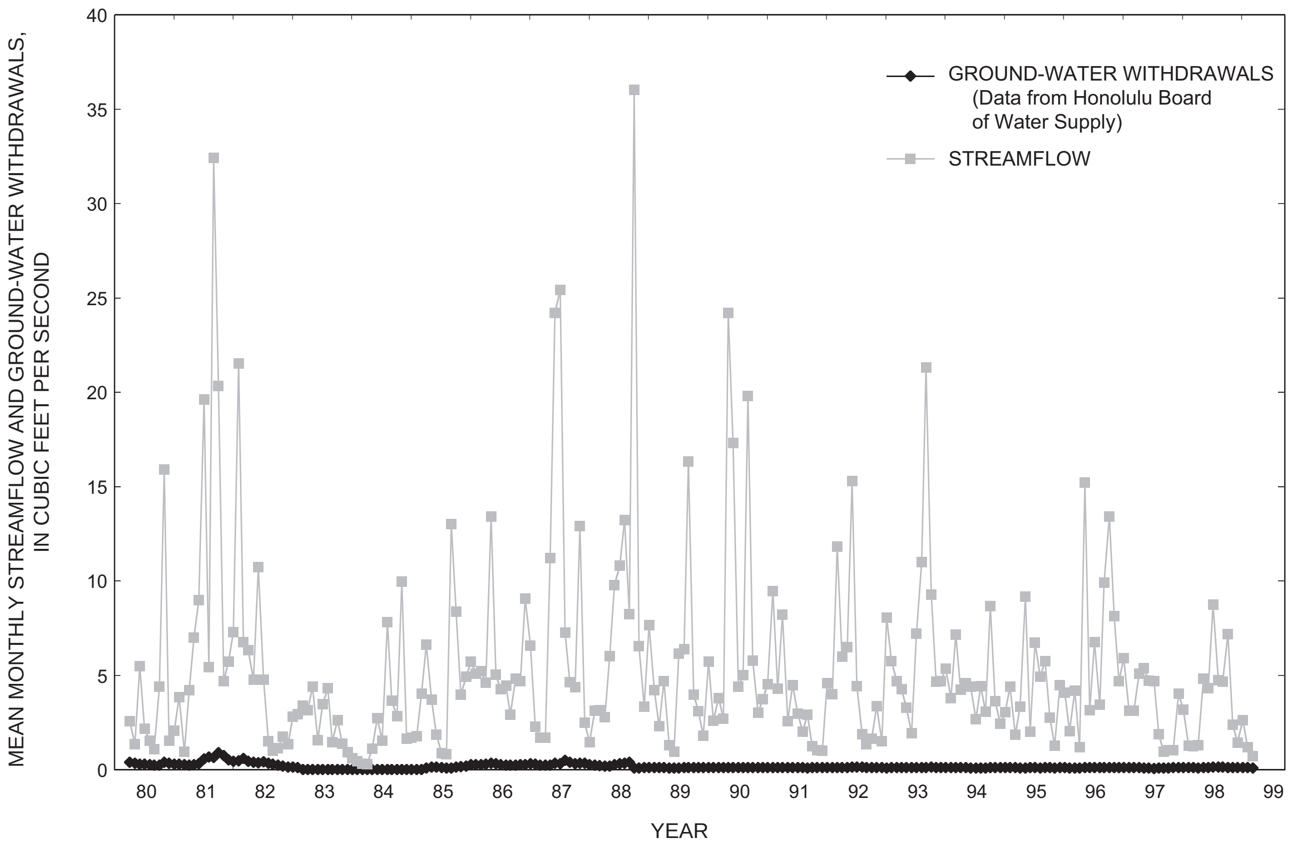

Figure 3. Mean monthly streamflow at streamflow-gaging station 16229000 and mean monthly upstream ground-water withdrawals, Oahu, Hawaii, June 1980–June 1999.

Hill (1996) also summarized previous studies of suspended-sediment yields from drainage basins along the Koolau Range. Suspended-sediment yields on the leeward side of the Koolau Range ranged from 24 to 1,770 (tons/mi^2)/yr while yields from windward drainage basins ranged from 8.6 to 1,400 (tons/mi^2)/yr. Hill (1996) derived two regression equations using the previously published suspended-sediment yields and before-construction suspended-sediment yields from gages in this study. These two equations, one for leeward basins and one for windward basins, can be used for estimating suspended-sediment yields from available streamflow data along the Koolau Range.

No previous studies of hydrologic effects of highway construction are available for Oahu or other similar central Pacific islands. Investigations from other locations, however, can provide some indication of the potential effects of road building. Studies dealing with streamflow changes attributable to construction of logging roads in the Pacific Northwest region of the continental United States showed that peak flows significantly increased only if roads and other compacted surfaces constituted at least 12 percent of drainage basin area (Harr and others, 1975; Ziemer, 1981; and King and Tennyson, 1984). These studies were conducted in small, less than 0.57 mi^2, drainage basins where rainfall was the dominant form of precipitation. These studies did not detect changes in other streamflow characteristics except for King and Tennyson (1984), who determined statistically significant changes in high flows, one increasing and one decreasing, in two out of seven basins monitored. Both basins had about 4 percent of their area affected by logging road construction.

Several studies have evaluated changes in sediment loads following highway construction in small drainage basins located in the eastern United States. Vice and others (1969) studied a 4.54 mi^2 drainage basin with 11 percent of the area affected by highway construction and 30 percent by farming and concluded that 85 percent of the total sediment load was due to highway construction. Eckhardt (1976) monitored a 1.99 mi^2 drainage basin with 1 percent of the area affected by highway construction and 38 percent by farming. Eckhardt (1976) attributed 50 percent of the suspended-sediment load to highway construction. Reed (1980) studied several small drainage basins ranging from 0.38 to 0.77 mi^2 in size with highway construction affecting from 5 to 12 percent of the basin areas and farming less than 10 percent and determined that 63 to 79 percent of the suspended-sediment load was due to highway construction. Ward and Appel (1988) monitored a 4.54 mi^2 relatively pristine drainage basin with 6 percent of the basin area disturbed by highway construction, and attributed 50 percent of the suspended-sediment load to highway construction. Ward and Appel (1988) also monitored a much larger 862 mi^2 drainage basin, and could not detect any changes in suspended-sediment load due to highway construction in the larger basin.

A statistical summary of hydrologic and water-quality data collected in the H-3 study area for water years 1983–89 was presented in Wong and Hill (1992). Wong and Young (2001) presents an updated statistical summary of hydrologic and water-quality data through water year 1999. This summary presented annual rainfall, streamflow, suspended-sediment loads, particle size, and concentrations, and water-quality data from streamflow and suspended-sediment gaging stations in the H-3 study area.

Additional background information on the H-3 Highway study area can be found in the many Environmental Impact Statements (EIS) such as U.S. Department of Transportation, Federal Highway Administration, and State of Hawaii Department of Transportation (1987). Information on individual drainage basins in the study area have been presented in other studies. Izuka (1992) discusses the geology and low-flow characteristics of North Halawa Valley. Hill and DeCarlo (1991) analyze sediment mineralogy and suspended-sediment concentrations before and during highway construction in North Halawa and Haiku Valleys using data from 1983–89. Hillslope soil-erosion rates were determined for North Halawa Valley by Hill and others (1997). A sediment budget and an analysis of sediment budget errors using sediment fingerprinting techniques for North Halawa Valley can be found in Hill and others (1998). This study concluded that 33 percent of the fine (less than 62 micron) suspended-sediment load in water year 1991 and 90 percent of the fine suspended-sediment load in water year 1992 were due to highway construction (Hill and others, 1998). An analysis of the sedimentation of Waimaluhia Reservoir can be found in Wong (2001) which concludes that the rate of sedimentation from 1983 to 1998 did not exceed the design rate of 2.0 acre-ft per year.

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APPROACH

The approach used in this study is a statistical comparison of data collected before and after highway construction with data collected during construction and a comparison of data collected before construction with data collected after construction. The first two comparisons were done to determine the effects of construction on streamflow and suspended-sediment loads in the affected basins, and the last comparison was done to see if streamflow and suspended-sediment loads after construction had returned to before-construction levels. Streamflow 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, and the last day of construction was used to define the periods during and after construction (tables 2 and 3). These

Table 3. Before, during, and after construction periods at streamflow-gaging stations in the H-3 Highway study area, Oahu, Hawaii

Station	Before construction			During construction			After construction		
	Start	End	Number of days	Start	End	Number of days	Start	End	Number of days
16225800	--	--	0	04/05/91	09/30/97	2,371	10/01/97	09/30/99	730
16226200	02/01/83	11/01/87	1,735	11/02/87	12/12/97	3,694	12/13/97	09/30/99	657
16265600	02/01/83	02/21/83	21	02/22/83	06/30/92	3,417	07/01/92	09/30/97	1,918
16270900	04/01/84	06/18/89	1,905	06/19/89	12/22/95	2,378	12/23/95	06/30/98	921
16272200	10/01/80	02/21/83	874	02/22/83	12/22/95	4,687	12/23/95	09/30/98	1,013
16273950	10/01/87	03/05/89	523	03/06/89	12/22/95	2,482	12/23/95	06/30/98	921
16275000[1]	10/01/82	10/23/88	2,215/767[1]	10/24/88	11/30/94	2,229	12/01/94	09/30/98	1,400

[1] Sediment data at station 16275000 are discontinuous; sediment data are available for 12/01/83 to 09/30/84 and from 07/20/87 to 09/30/98

periods are not the same at all stations because start dates for data collection and for construction varied. Stream-gaging stations 16226200, 16270900, 16272200, 16273950 and 16275000 have reasonably long periods of data before and during construction (table 3). Stream-gaging station 16265600 has only a few days of before-construction data, and this short period is not sufficient for the before- and during-construction analyses described below. Streamflow and suspended-sediment data are available only after construction began at stream-gaging station 16225800 and so cannot be used to compare streamflow and suspended-sediment loads before and during construction.

Statistical procedures used in data analysis were designed to remove the variations in streamflow and suspended-sediment loads that resulted from changes in rainfall. Since 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 highway construction or other land-use effects. By minimizing the effects of rainfall fluctuations, the remaining variability could then be attributed to land-use effects. Effects of rainfall were minimized by using analysis of covariance procedures (Helsel and Hirsch, 1992; Wildt and Ahtola, 1978). Analysis of covariance is a linear 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, during and after, and before and after construction of the H-3 Highway. The use of the term “time period” in this report refers to the periods before, during, and after construction listed in table 3. One of the variables, known as the explanatory variable or covariate, represented natural variations resulting from rainfall, with no effect from highway construction. The other variable is known as the 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. Hydrologic significance was tested by comparing observed streamflows with estimates of streamflow derived from the regression equations determined by analysis of covariance. Differences larger than the accuracy of the streamflow data were considered significant. Accuracy in this context is equivalent to the margin of error. Accuracy of streamflow records are rated on an annual basis as “good,” “fair,” or “poor” (Hill and others, 2000). 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 of the true values at all streamflow-gaging stations. Because hydrologic significance was determined from regression estimates based on streamflow at index (covariate) station 16229000, the accuracy of streamflow at station 16229000, 15 percent, was used as the accuracy of all streamflow regression relationships. The combined accuracy of streamflow data at the study streamflow-gaging stations (15 percent) with the regression estimates (15 percent) is 21 percent. The 21 percent accuracy was computed as the square root of the sum of squares of each accuracy value (Benjamin and Cornell, 1970; Rabinovich, 1995). Streamflow changes that are within the accuracy limit of 21 percent cannot be considered hydrologically significant, although they may be statistically significant.

A similar test was done with the suspended-sediment data. Only if both statistical and hydrological significance criteria were met, would any changes in either streamflow or suspended-sediment data be attributed to highway construction. The applications of this method are described more fully in the sections on streamflow and suspended-sediment analyses below.

Results of all 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 statistical hypothesis tests to 0.05.

Data Collection

Rainfall data was collected at stream-gaging stations 16226000, 16226200, 16265600, 16270900, and in Haiku Valley (figs. 1 and 2). Both tipping bucket and float-type rain gages were used with standard National Weather Service 8-in. diameter rain collectors. Streamflow data were collected at stations 16225800, 16226000, 16226200, 16229000, 16265600, 16270900, 16272200, 16273950, and 16275000 using continuous gage-height recorders and periodic measurements of streamflow following standard practices for streamflow data collection (Rantz and others, 1982). Suspended-sediment samples were collected at stream-gaging stations 16225800, 16226200, 16265600, 16270900, 16272200, 16273950, and 16275000 using both single point automatic suspended-sediment samplers and periodic depth-integrated cross-sectional samples using the equal-width-increment method (Edwards and Glysson, 1999). Suspended-sediment concentrations were determined at the U.S. Geological Survey office in Honolulu and suspended-sediment loads were computed using suspended-sediment concentrations and streamflow records, as described by Porterfield (1972). Additional details on data collection can be found in Wong and Young (2001).

Table 4. Basin area-weighted median annual rainfall at drainage basins in and near the H-3 Highway study area, Oahu, Hawaii

[Basin area-weighted median rainfall values from Wong (1994); *, computed by Wong (1994) but not previously published]

Station	Basin area-weighted median annual rainfall in inches
16226200	118*
16229000	120
16270900	108
16272200	92*
16275000	108

Streamflow Analysis

Streamflow at stream-gaging stations 16225800, 16226200, 16265600, 16270900, 16272200, 16273950, and 16275000 was used as the response variable and streamflow at index stream-gaging station 16229000 (figs. 1 and 2) was used as the covariate in the analysis of covariance. As previously discussed streamflow at station 16229000 is unaffected by H-3 Highway construction, diversions, or change in land use. Variations in streamflow at station 16229000 were therefore primarily the result of rainfall variations. Rainfall distribution, as determined by area-weighted average of median annual rainfall (Wong, 1994), is similar among all study basins and the index station (table 4). Therefore, the use of streamflow data from streamflow-gaging station 16229000 as covariate would account for the streamflow variations at the study stations due to rainfall.

Mean daily streamflow data were separated into low- and high-flow classes before analysis to permit separate evaluations of construction effects on low flows and high flows. The daily streamflow with an exceedance probability of 10 percent at station 16229000, which was determined by Hill (1996) to be 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. Data sets varied in size depending on station and time period but for low-flow analysis all data sets were greater than 1000 data points in size and for high flow analysis all were greater than 100 data points in size. Another analysis was done using annual peak flows, which are the highest instantaneous peak flows during a water year. High-flow and peak-flow data were log-transformed before analysis to improve regression relations 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 stations 16225800 and 16226200 could not be log-transformed and because log-transformation did not significantly improve regression relations at the other stations, as determined by examination of regression residuals.

The analysis of covariance tested whether time period (before, during, and after construction) accounted for variations in streamflow at stations 16225800, 16226200, 16265600, 16270900, 16272200, 16273950, and 16275000 by comparing regression equations relating streamflow at these stations to streamflow at the index station 16229000 for each time period. A comparison of low streamflow before and during construction at station 16275000 is presented below as an example. Similar analyses were done to compare the other time periods at this station: during and after, and before and after construction. These three comparisons were then repeated for each of the other stations.

The first equation, simply relates the response variable to the covariate, and is expressed as

$$Q_{16275000} = A + (B \times Q_{229000}), \tag{1}$$

where $Q_{16275000}$ represents the response variable (streamflow at stream-gaging station 16275000), $Q_{16229000}$ represented the covariate (low streamflow on the same day at index station 16229000), 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

$$Q_{16275000} = A + (B \times Q_{16229000}) + (C \times Z), \tag{2}$$

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 16229000. This third equation was expressed as

$$Q_{16275000} = A + (B \times Q_{16229000}) + (C \times Z) + (D \times W), \tag{3}$$

or as

$$Q_{16275000} = A + (B \times Q_{16229000}) + (C \times Z) + (D \times Z \times Q_{16229000}), \tag{4}$$

where D was a regression coefficient. The interaction term was zero when Z equalled zero, 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 period 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. Changes in intercept and slope can be positive or negative.

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 16229000), 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 (critical values of the F-distribution can be found in many statistical textbooks such as 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 16229000), 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, 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.

The analysis of covariance on annual peak flow data was slightly different from the approach used on daily mean streamflow for the low- and high-flow classes, described previously, because of the limited amount of annual peak flow data. The analysis of covariance was conducted using annual peak flows at gaging stations 16226000, 16270900, and 16275000 as the response variable with peak flows at 16229000 as the covariate. The peak flow analysis was only conducted with data from stations 16226000, 16270900, and 16275000 because the number of annual peaks available for analysis at these stations was greater than 20. A smaller number of data points was considered inadequate for statistical analysis due to potential inaccuracies in using statistical tests on small data sets. Analysis of covariance was not conducted with data from station 16272200 because peak flows at this site are regulated by the upstream flood control reservoir. The peak flow data were divided into only two categories, before construction and during and after construction, rather than into three categories, before, during, and after construction as was done with the daily mean streamflow data. This was done due to the limited number of annual peak flows available. Annual peak flow data extending back to 1971 were used so that more than 20 annual peaks were available for the analyses and to give a roughly equal number of before-construction to during- and after-construction annual peaks. The actual number of annual peak flows at stations 16226000, 16270900, and 16275000 were 29, 26, and 24 respectively (table 5).

Suspended-Sediment Analysis

Analysis of covariance was used to assess changes in relations between streamflow and suspended-sediment loads at stream-gaging stations 16225800, 16226200, 16265600, 16270900, 16272200, 16273950, and 16275000 due to 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. 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, or the value of zero for data during highway construction and 1 for data after 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*.

Mean daily streamflow and daily total suspended-sediment load data were transformed to base 10 logarithms before analysis. A number of daily total suspended-sediment loads were reported as 0 tons in two situations: (1) loads were 0 tons on many days at stations 16225800 and 16226200 when streamflow at

Table 5. Annual instantaneous peak flow at streamflow-gaging stations in and near the H-3 Highway study area, Oahu, Hawaii, water years 1971–99

[--, no data; shaded values represent annual peak flows occurring during periods of highway construction]

	Instantaneous peak flow in cubic feet per second								
	Station								
Water Year	**16225800**	**16226000**	**16226200**	**16229000**	**16265600**	**16270900**	**16272200**	**16273950**	**16275000**
1971	--	1,750	--	1,970	--	651	--	--	4,420
1972	--	538	--	1,470	--	180	--	--	328
1973	--	153	--	137	--	6	--	--	30
1974	--	1,360	--	1,100	--	159	--	--	565
1975	--	950	--	1,420	--	180	--	--	721
1976	--	758	--	822	--	112	--	--	456
1977	--	593	--	1,070	--	96	968	--	203
1978	--	295	--	316	--	56	217	--	--
1979	--	453	--	714	--	81	439	--	--
1980	--	5,470	--	2,630	--	400	1,500	--	--
1981	--	872	--	1,010	--	150	715	--	--
1982	--	1,970	--	5,120	--	548	916	--	--
1983	--	695	--	608	--	250	281	--	165
1984	--	299	330	218	--	--	142	--	33
1985	--	528	710	1,100	842	96	645	--	419
1986	--	734	868	782	713	232	470	--	650
1987	--	916	1,020	2,160	1,160	299	1,430	--	743
1988	--	1,140	1,180	2,070	1,310	--	1,650	207	754
1989	--	884	868	1,080	697	260	994	152	640
1990	--	836	880	878	486	132	366	86	700
1991	--	1,320	1,780	2,840	936	247	970	118	743
1992	468	614	860	926	443	231	284	90	732
1993	307	217	294	1,270	856	232	850	116	290
1994	460	1,100	1,640	1,790	670	380	1,070	106	710
1995	275	335	501	1,100	611	144	615	94	160
1996	403	422	778	1,060	2,800	957	1,760	181	640
1997	329	354	849	834	566	302	538	--	754
1998	296	413	423	210	--	58	266	32	189
1999	335	665	496	576	--	--	187	--	133

those stations 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 (Amemiya, 1985; 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 tons/day. Randomly selected subsamples of 500 suspended-sediment load-streamflow data pairs were used for the analysis of covariance to avoid high correlation between streamflow and *Z*, the variable representing construction, especially if streamflow was affected by construction activities. A low correlation between streamflow and *Z* (construction) would validate the implicit assumption in analysis of covariance that independent variables, streamflow and *Z* (construction) in this case, are not correlated (Wildt and Ahtola, 1978).

The significance of the regression coefficient for *Z* was tested using a likelihood ratio (Cohn, 1988), which is similar to the t-test used to evaluate the coefficient for *Z* in the analysis of covariance done on streamflow described previously. 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, 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, the overall effect of time period on the relation between streamflow and suspended-sediment load was considered to be significant.

STREAMFLOW BEFORE, DURING, AND AFTER CONSTRUCTION

Hydrologic conditions during the study.--Annual streamflow was generally higher during the years of high rainfall (tables 6 and 7). For much of the H-3 Highway study area, the years of highest streamflow during the study period coincided with years of high rainfall (table 6) and with the during highway-construction period (table 3). Records available for streamflow-gaging stations 16226000 and 16272200 show that annual streamflow was higher prior to highway construction in 1982 than for any year during the 1983–99 highway construction period (table 7). Average mean daily streamflow per unit area was higher before construction than during or after construction at stations 16272200 and 16273950, and higher during construction than either before or after construction at the remaining stations (fig. 4). There were no before construction data collected at station 16225800 and just a few days at station 16265600 (table 3).

Flood frequency.--Recurrence intervals for annual instantaneous peak flows were computed using methods of the Interagency Advisory Committee on Water Data (1982) for three gaging stations in the study area with long (more than 30 years) periods of record: stream-gaging station 16226000 in North Halawa Valley (fig. 1), station 16270900 Luluku Stream in the Kamooalii drainage basin (fig. 2) and station 16275000 in Haiku Valley (fig. 2). Recurrence intervals for annual peak flows at station 16226000 ranged from 1 to 2 years throughout the study periods. Annual peak flows at station 16270900 had recurrence intervals of 2 years before construction, 1 to 5 years during construction, and from 1 to 50 years after construction. At station 16275000, before construction recurrence intervals ranged from 1 to 2 years, construction-period

Table 6. Annual and average rainfall at rain-gaging stations in and near the H-3 Highway study area, Oahu, Hawaii, water years1983–99

[All values in inches; NWS, National Weather Service; --, no data; P, partial year of record, more than one month of record missing; e, estimated annual total, one or more days were estimated, data were estimated by comparison with nearby rain gages; Numbers below gage numbers or names are 4 digit State key numbers assigned to rain gages in Hawaii by the Commission on Water Resource Management, Department of Land and Natural Resources, State of Hawaii]

	USGS Stations					NWS Stations		
Drainage basin	North Halawa	North Halawa	R.Branch Kamooalii	Luluku	Haiku	North Halawa	Kamooalii	R.Branch Kamooalii
Water year	16226000 (772.1)	16226200 (771.9)	16265600 (781.9)	16270900 (781.11)	Haiku (839.3)	Halawa (771.2)	Luluku (781.7)	Pali Golf Course (788.1)
1983	65.4	P	P	--	--	P	P	59.4
1984	44.1	23.5	38.9	P	--	P	41.9	37.8
1985	61.6	40.7	63.9	66.8	--	43.2	71.2	55.8
1986	60.9	32.9	59.2	66.2	P	36.3	74.2	53.3
1987	68.3	33.8	67.2	66.7	75.4	38.1	e76.1	62.5
1988	90.6	56.5	86.8	95.1	113	49.8	98.7	130
1989	e91.2	55.5	84.1	87.2	105	e59.1	e110	103
1990	66.5	35.3	62.4	62.8	92.0	e40.1	e80.0	P
1991	80.2	41.2	68.5	59.9	e101	e51.7	P	80.1
1992	52.8	27.3	42.2	e55.9	69.0	36.5	e75.9	50.1
1993	e58.7	e33.5	P	61.6	69.5	37.4	76.2	110
1994	P	23.6	P	71.2	91.2	e39.0	91.5	84.6
1995	49.4	e43.8	e40.2	49.1	64.2	e29.2	P	68.8
1996	53.7	43.4	e60.1	73.7	83.7	e49.8	92.4	97.2
1997	63.8	61.0	e75.9	e81.5	99.6	P	e105	109
1998	33.3	23.7	P	44.7	48.6	e26.9	P	40.7
1999	35.9	31.8	--	--	--	e31.9	56.9	P
Average[1]	61.0	38.0	62.4	67.7	84.4	40.6	80.8	76.2

[1]Average is for complete years only for the period 1983–99

recurrence intervals were all about 2 years, and after construction recurrence intervals ranged from 1 to 2 years. The majority of peak flows during the study period were small enough that they recur on average every 2 years. The highest peak flows based on recurrence intervals during the study period occurred at station 16270900 in the Kamooalii drainage basin, during the after construction period in January 1996. The peak at station 16270900 was caused by a locally intense storm and had a recurrence interval of 50 years based on at station frequency analysis (Interagency Advisory Committee on Water Data, 1982). On the basis of regional frequency analysis (Wong, 1994), the recurrence interval for the 1996 peak at station 16270900 was about 25 years.

The highest annual peak flow at station 16226000 was recorded prior to highway construction in 1980 (table 5). The highest peak flow during construction occurred in 1991. At station 16270900 the highest peak flow occurred after construction in 1996. The second highest peak flow occurred before construction in 1971. At station 16275000 peak flows were higher before and after construction in 1971, 1988, and 1997 than during construction (table 5). Streamflow peaks during the study period at stations with shorter periods of record such as stations 16265600 and 16272200 in the

Table 7. Annual total streamflow at streamflow-gaging stations in and near the H-3 Highway study area, Oahu, Hawaii, water years 1981–99

[--, no data; shaded values represent data collected during periods of highway construction]

Water year	Annual total streamflow in cubic feet per second								
	Station								
	16225800	16226000	16226200	16229000	16265600	16270900	16272200	16273950	16275000
1981	--	918	--	1,320	--	--	3,140	--	--
1982	--	4,300	--	4,400	--	--	8,040	--	--
1983	--	964	[1]203	1,300	[1]267	--	4,090	--	877
1984	--	517	525	745	122	44[2]	1,600	--	520
1985	--	827	969	1,170	284	152	2,290	--	604
1986	--	1,590	1,580	1,840	406	150	2,940	--	674
1987	--	1,440	1,540	1,930	612	327	3,760	--	790
1988	--	3,140	3,700	3,120	986	508	6,070	1,020	1,270
1989	--	3,040	3,640	3,350	1,040	532	5,930	1,050	1,420
1990	--	1,670	1,840	1,720	532	488	4,280	847	888
1991	[2]458	2,740	3,440	3,170	762	737	5,000	938	1,230
1992	818	1,030	1,135	1,430	308	471	3,030	828	806
1993	1,020	1,410	1,480	1,850	605	394	3,610	860	738
1994	1,560	2,150	2,449	2,540	609	519	4,240	838	941
1995	708	1,030	1,294	1,430	216	606	2,600	704	618
1996	801	1,260	1,640	1,540	504	520	3,580	722	735
1997	1,200	1,890	2,703	2,370	721	554	5,370	894	1,030
1998	506	609	824	1,050	--	[3]341	2,730	[3]540	696
1999	565	1,220	1,213	1,340	--	--	1,800	--	566

[1]Data from February to September

[2]Data from April to September

[3]Data from October to June

Kamooalii drainage basin were highest during construction in 1988 and after construction in 1996. The highest streamflow peaks at station 16273950 occurred both before and after construction in 1988 and 1996, respectively. At the other two stations in the North Halawa valley, stations 16225800 and 16226200, streamflow peaks were higher during construction in 1988, 1991, and 1994 at station 16226200 and in 1992 and 1994 at station 16225800. In general, streamflow peaks during construction were higher in the North Halawa and Kamooalii drainage areas and lower in the Haiku and South Fork Kapunahala drainage areas.

Streamflow Changes due to Construction

Low Flows

The changes in regression intercepts and slopes for the analysis of covariance shown in table 8 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 8, are constants that increase (positive coefficients) or decrease (negative coefficients) predicted flows equally over the entire range of data. Changes in slope, which are equal to the coefficients for variable *W* listed in table 8, result in changes in estimated streamflow that are proportional to streamflow at stream-gaging station 16229000.

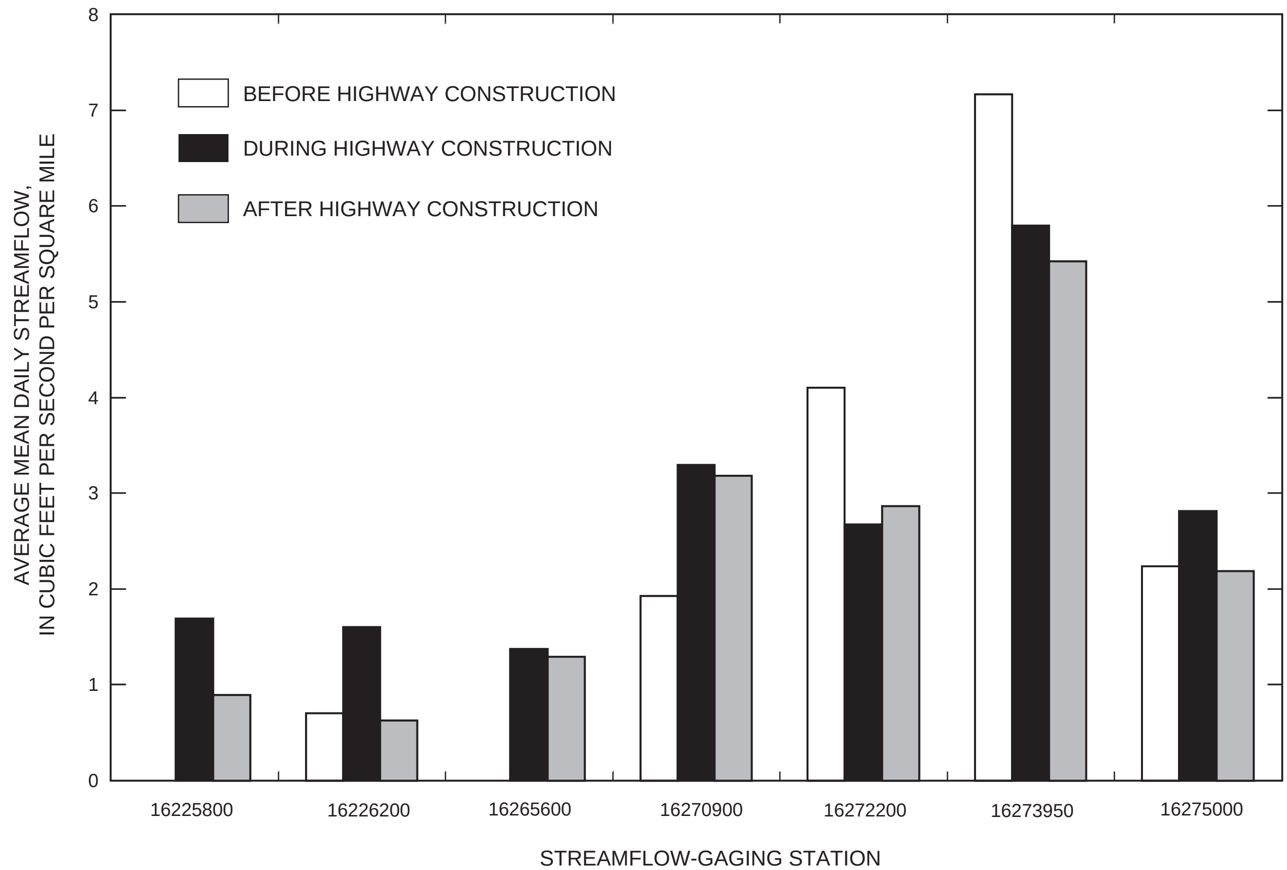


Figure 4. Average mean daily streamflow per unit area for the before, during, and after highway construction periods at streamflow-gaging stations in the H-3 Highway study area, Oahu, Hawaii, 1981–99.

Before and during construction.--Relations between low flows at stream-gaging stations 16226200, 16270900, 16272200, 16273950, and 16275000 and low flows at index station 16229000 changed significantly during the highway construction period for the before and during highway construction analysis of covariance (table 8). Regression intercepts were significantly different at stations 16226200, 16270900, and 16273950; the intercept decreased at stations 16226200 and 16273950 and increased at station 16270900. Regression slopes were significantly different at stations 16270900, 16272200, 16273950, and 16275000; slope increased at station 16275000, and decreased at stations 16270900, 16272200, and 16273950.

To determine if the low-flow changes detected using analysis of covariance were hydrologically significant, changes in low flows were estimated by applying before highway-construction regression coefficients for slope and intercept from the analysis of covariance (table 8) to the during highway-construction period low flows at station 16229000. The estimated low flows represent low flows that would be expected if relations between streamflows at stations 16226200, 16270900, 16272200, 16273950, and 16275000 and the index station 16229000 were unchanged by construction (table 9). 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 procedure accounts for the effects of rainfall by using streamflow at the index station as a covariate. Percent differences were computed by equation 5 and represent the percent change of the during- or after-construction low flows attributed to construction.

Table 8. Analysis of covariance results relating concurrent daily mean streamflow at streamflow-gaging stations in the H-3 Highway study area to the index station 16229000 for the before, during, and after highway construction periods, Oahu, Hawaii

[Daily mean streamflows at station 16229000 and at stations 16225800, 16226200, 16265600, 16270900, 16272200, 16273950, and 16275000 were used as the covariate and response variables, respectively; *Z* was set to zero for before construction and 1 for construction; or zero for construction and 1 for after construction, *W* was set to (*Z* × streamflow at station 16229000); 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	Regression coefficients for: Intercept	Slope	*Z*	*W*	t-ratio for significance of *Z*	F-statistics for significance of: *W*	*Z + W*
Before and during highway construction periods							
Low flow (mean daily streamflow less than or equal to 10.0 ft^3/s at station 16229000)							
16226200	-1.43	1.17	-0.42*	0.04	-2.86*	0.69	7.04*
16270900	0.27	0.11	0.70*	-0.02*	30.0*	5.70*	1200*
16272200	5.15	2.07	-0.39	-1.04*	-1.72	292*	492*
16273950	1.98	0.11	-0.08*	-0.04*	-2.02*	22.9*	75.6*
16275000	1.29	0.15	-0.07	0.04*	-1.87	16.3*	11.2*
High flow (mean daily streamflow greater than 10.0 ft^3/s at station 16229000)							
16226200	0.10	0.94	-0.38	0.29	-1.75	3.38	1.71
16270900	-0.88	0.86	0.28*	-0.11	2.55*	1.92	16.7*
16272200	0.57	0.67	-0.37*	0.17*	-3.15*	4.26*	15.4*
16273950	-0.13	0.54	-0.03	-0.03	-0.33	0.16	5.90*
16275000	-0.59	0.94	-0.03	0.07	-0.24	0.70	4.12*
During and after highway construction periods							
Low flow (mean daily streamflow less than or equal to 10.0 ft^3/s at station 16229000)							
16225800	-0.97	0.72	0.17*	-0.05*	2.08*	5.83*	3.61*
16226200	-1.85	1.21	0.16	0.14*	0.73	4.00*	9.06*
16265600	0.43	0.13	-0.22*	0.04	-3.14*	3.42	5.86*
16270900	0.97	0.09	-0.11*	0.01	-3.55*	2.94	8.74*
16272200	4.76	1.03	-0.16	0.42*	-0.82	63.5*	81.9*
16273950	1.90	0.07	-0.17*	0.02*	-7.10*	6.53*	43.2*
16275000	1.22	0.19	0.07	-0.02*	1.56	4.70*	2.44
High flow (mean daily streamflow greater than 10.0 ft^3/s at station 16229000)							
16225800	-0.33	1.10	0.01	-0.04	0.17	1.36	0.74
16226200	-0.28	1.23	0.04	-0.01	0.07	0.00	0.10
16265600	-1.36	1.30	-0.02	0.03	-0.06	0.04	0.19
16270900	-0.60	0.75	0.03	0.02	0.20	0.04	2.42
16272200	0.21	0.84	0.04	0.05	0.22	0.11	4.82*
16273950	-0.16	0.52	-0.11	0.11	-0.85	1.29	1.73
16275000	-0.62	1.02	-0.03	-0.03	-0.17	0.07	2.79
Before and after highway construction periods							
Low flow (mean daily streamflow less than or equal to 10.0 ft^3/s at station 16229000)							
16226200	-1.43	1.17	-0.27	0.17*	-1.51	8.96*	5.36*
16270900	0.27	0.11	0.59*	-0.00	24.2*	0.00	887*
16272200	5.15	2.07	-0.54	-0.62*	-1.54	40.8*	87.6*
16273950	1.98	0.11	-0.25*	-0.03*	-6.17*	7.04*	122*
16275000	1.29	0.15	-0.00	0.01	-0.04	2.37	3.33*
High flow (mean daily streamflow greater than 10.0 ft^3/s at station 16229000)							
16226200	0.10	0.94	-0.34	0.29	-0.77	0.65	0.35
16270900	-0.88	0.86	0.32	-0.09	1.54	0.33	14.5*
16272200	0.57	0.67	-0.32	0.21	-1.77	2.54	1.85
16273950	-0.13	0.54	-0.14	0.08	-0.93	0.52	0.98
16275000	-0.59	0.94	-0.06	0.04	-0.31	0.08	0.05

$$\text{Percent change} = [(OBS - EST)/ EST] \times 100 \qquad (5)$$

Where *OBS* represents the observed low flow and *EST* the estimated low flow. Estimated changes in low flows during the highway-construction period range from a decrease of 31 percent of observed low flows at station 16272200 to an increase of 108 percent at station 16270900 (table 9). Only the estimated changes at stations 16270900 and 16272200 were greater than the limits of accuracy for the streamflow records used in the analyses which was 21 percent. The estimated changes for stations 16226200, 16273950, and 16275000 were 21 percent or less (table 9) and therefore cannot be considered hydrologically significant.

During and after construction.--Relations between low flows at all streamflow-gaging stations except 16275000 and low flows at index station 16229000 changed significantly after the highway-construction period in the during and after construction analysis (table 8). Regression intercepts were significantly different at stations 16225800, 16265600, 16270900, and 16273950; the intercept decreased at stations 16265600, 16270900, and 16273950 and increased at station 16225800. Regression slopes were significantly different at stations 16225800, 16226200, 16272200, 16273950, and 16275000; slope increased at stations 16226200, 16272200, and 16273950, and decreased at stations 16225800 and 16275000. Only the change at station 16226200 was hydrologically significant with low flows increasing by an estimated 47 percent after construction (table 9).

Before and after construction.--Relations between low flows at all stream-gaging stations and low flows at index station 16229000 changed significantly after the highway-construction period in the before and after construction analysis (table 8). Regression intercepts were significantly different at stations 16270900, and 16273950; the intercept decreased at stations 16273950 and increased at station 16270900. Regression slopes were significantly different at stations 16226200, 16272200, and 16273950; slope increased at station 16226200 and decreased at stations 16272200 and 16273950. Only the change at station 16270900 was hydrologically significant with low flows increasing by an estimated 99 percent after construction compared to before construction (table 9).

High and Peak Flows

Before and during construction.--Relations between high flows at streamflow-gaging stations 16270900, 16272200, 16273950, and 16275000 and high flows at index station 16229000 changed significantly during the highway-construction period in the before and during construction analysis (table 8). The intercept increased at station 16270900 and decreased at station 16272200. The slope increased at station 16272200. Neither *Z* nor *W* were significant individually at stations 16273950 and 16275000, but their combined effect was significant.

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 1.08 to 1.80 (table 9) and were used to increase the back-transformed intercept prior to estimating high flows. Percent changes in high flows were computed using equation 5 with *OBS* being the observed high flow and *EST* equal to the estimated high flow. Only the change at station 16275000 was statistically and hydrologically significant with high flows increasing by an estimated 25 percent during construction (table 9).

Estimates of changes in high flows during highway construction required extrapolation of the before-construction regression equation beyond the range of before-construction high flow data at index station 16229000 only at station 16226200. Extrapolation was defined as a daily mean high flow being more than 100 percent greater than the highest daily mean high flow used to compute the before highway-construction regression equation at index station 16229000. The use of these estimates requires the assumption that the before construction relation between streamflow at index station 16229000 and streamflow at station 16226200 remains linear at flows higher than any observed during the before construction period. Hill (1996) checked this assumption by comparing annual streamflow at station 16229000 with long term annual streamflow at station 16226000 using double-mass curves (Searcy and Hardison, 1960). Hill (1996) found no deviations from a linear pattern, so the extrapolation was considered reasonable for station 16226200, which is about 1.3 mi downstream of station 16226000 (fig. 1).

Table 9. Estimated changes in streamflow at streamflow-gaging stations for the during and after highway-construction periods in the H-3 Highway study area, Oahu, Hawaii, 1983–99

[Estimated streamflows were computed by applying before and during construction regression coefficients listed in table 10 to daily mean streamflows at station 16229000 during and after 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); * indicates significant hydrologic effect of period because the difference is greater than the accuracy of the streamflow records which is 21 percent]

During highway construction

Station	Observed streamflow (ft^3/s)	Estimated streamflow using before construction relation equation (ft^3/s)	Equation standard error of estimate	Equation bias correction factor	Difference between observed and estimated streamflow (percent)
Low flow (mean daily streamflow less than or equal to 10.0 ft^3/s at station 16229000)					
16226200	6,900	7,910	2.90	--	–13
16270900	2,730	1,310	0.42	--	108*
16272200	33,500	48,400	3.35	--	–31*
16273950	4,780	5,260	0.38	--	–9
16275000	3,740	3,600	0.65	--	4
High flow (mean daily streamflow greater than 10.0 ft^3/s at station 16229000)					
16226200	16,800	13,700	0.355	1.13	23*
16270900	713	596	0.236	1.22	20
16272200	14,100	15,600	0.249	1.12	–10
16273950	967	1,110	0.168	1.08	–13
16275000	2,340	1,870	0.252	1.20	25*

After highway construction

Station	Observed streamflow (ft^3/s)	Estimated streamflow using during construction relation equation (ft^3/s)	Equation standard error of estimate	Equation bias correction factor	Difference between observed and estimated streamflow (percent)
Low flow (mean daily streamflow less than or equal to 10.0 ft^3/s at station 16229000)					
16225800	605	569	1.65	--	6
16226200	931	634	2.98	--	47*
16265600	1,280	1,470	1.33	--	–13
16270900	1,010	1,060	0.44	--	–5
16272200	8,320	7,300	2.99	--	14
16273950	1,700	1,800	0.34	--	–6
16275000	2,300	2,320	0.66	--	–1
High flow (mean daily streamflow greater than 10.0 ft^3/s at station 16229000)					
16225800	466	522	0.352	1.26	–11
16226200	710	692	0.372	1.25	3
16265600	1,460	1,130	0.498	1.80	29*
16270900	279	212	0.211	1.11	32*
16272200	2,710	2,010	0.259	1.20	35*
16273950	300	268	0.172	1.08	12
16275000	659	716	0.259	1.18	–8

Table 9. Estimated changes in streamflow at streamflow-gaging stations for the during and after highway-construction periods in the H-3 Highway study area, Oahu, Hawaii, 1983–99--Continued

[Estimated streamflows were computed by applying before and during construction regression coefficients listed in table 10 to daily mean streamflows at station 16229000 during and after 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); * indicates significant hydrologic effect of period because the difference is greater than the accuracy of the streamflow records which is 21 percent]

After highway construction					
Station	**Observed streamflow (ft^3/s)**	**Estimated streamflow using before construction relation equation (ft^3/s)**	**Equation standard error of estimate**	**Equation bias correction factor**	**Difference between observed and estimated streamflow (percent)**
Low flow (mean daily streamflow less than or equal to 10.0 ft^3/s at station 16229000)					
16226200	931	845	2.34	--	10
16270900	1,010	507	0.34	--	99*
16272200	8,320	10,500	4.17	--	–21
16273950	1,700	1,980	0.37	--	–14
16275000	2,300	2,250	0.53	--	2
High flow (mean daily streamflow greater than 10.0 ft^3/s at station 16229000)					
16226200	710	626	0.283	1.13	13
16270900	279	176	0.268	1.22	58*
16272200	2,710	2,500	0.233	1.12	8
16273950	300	313	0.179	1.08	–4
16275000	659	610	0.270	1.20	8

Table 10. Analysis of covariance results relating instantaneous peak flow at streamflow-gaging stations in the H-3 Highway study area to index station 16229000 for the before, during, and after highway construction periods, Oahu, Hawaii, water years 1971–99

[Instantaneous peak flows at station 16229000 and at stations 16226000, 16270900, and 16275000 were used as the covariate and response variables, respectively; *Z* was set to zero for before-construction and 1 for during and after construction; *W* was set to (*Z* × instantaneous peak flow at station 16229000); peak flow data were log-transformed; * indicates significant effect of period on the basis of t-ratio or F-test; critical t-ratio is 2.05; critical F-values are 4.22 for significance of *W* and 3.37 for significance of *Z* and *W* together]

Before-construction and during- and after-construction periods							
	Regression coefficients for				t-ratio for significance	F-statistics for significance of	
Station	Intercept	Slope	*Z*	*W*	of *Z*	*W*	*Z* + *W*
16226000	0.77	0.71	-0.05	-0.00	-0.33	0.30	1.21
16270900	-1.30	1.16	0.50*	-0.00	2.61*	3.76	3.55*
16275000	-1.52	1.38	0.38	-0.00	1.87	4.18	2.15

During and after construction.--For the during and after highway-construction analysis, only the high flow relations between streamflow-gaging station 16272200 and index station 16229000 changed significantly. Neither *Z* nor *W* were significant individually at station 16272200, but their combined effect was significant. Both intercept and slope increased slightly (table 8) and estimated high flows increased by 35 percent at station 16272200 (table 9). High flows at stations 16270900 and 16265600 were both hydrologically significant (table 9) but not statistically significant (table 8).

Before and after construction.--For the before and after highway-construction analysis, only relations between high flows at streamflow-gaging station 16270900 and high flows at index station 16229000 changed significantly after construction (table 8). Again, neither *Z* nor *W* were significant individually, but their combined effect was. The intercept increased and slope decrease slightly at station 16270900 (table 8) and the estimated change in high flows increased by 58 percent (table 9).

Peak flows.--Relations between peak flows at stations 16226000, 16270900, and 16275000 and peak flows at index station 16229000 changed significantly only at station 16270900 (table 10). The regression intercept increased indicating an increase in peak flows at 16270900 during and after construction. Because annual peak flows are instantaneous, hydrologic significance could not be determined using the same procedure as for low- and high-flows.

Effects of Land-use Changes on Streamflow

Significant changes in streamflow between time periods are unlikely to have occurred as a result of random streamflow variations, and are probably the result of changes in drainage-basin conditions related to land-use activities. H-3 Highway construction is a possible cause of the changes in streamflow, but other activities, such as ground-water development, 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 affect low flows (Hirashima, 1963; 1971). The most likely activities that may have affected the ground-water flow system during and after construction of the H-3 Highway include municipal ground-water withdrawals and H-3 construction.

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 during the highway construction period in the drainage basins upstream of stream-gaging stations 16270900 and 16272200 (figs. 5 and 6). These increased withdrawals may have reduced low flows at these stations (Takasaki and Mink, 1985), but are unlikely to account for the increased low flows at station 16270900.

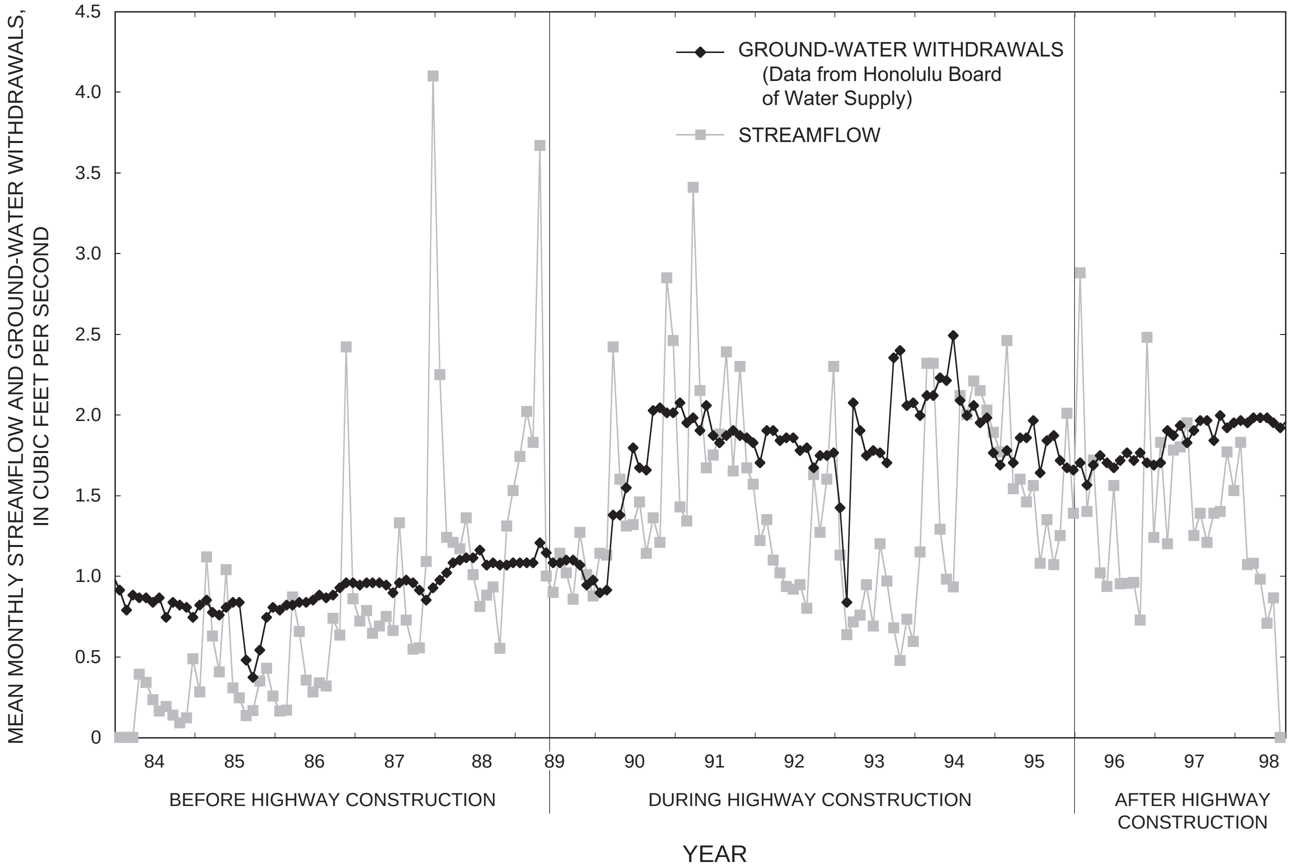


Figure 5. Mean monthly streamflow at streamflow-gaging station 16270900 and mean monthly upstream ground-water withdrawals, Oahu, Hawaii, April 1984 to June 1998.

A number of H-3 Highway construction activities could potentially affect low flows that are maintained by ground-water discharge. The excavation of highway tunnels in a ground-water recharge zone below the crest of the Koolau Range could increase or decrease low flows. Hill (1996) analyzed the ground-water seepage in the Trans-Koolau tunnels and determined that seepage from the tunnels would have only a minor effect, if any, on the streamflow in the study area. Activities such as vegetation removal, reduced agricultural streamflow diversions, irrigation for highway landscaping, and highway runoff from compacted or paved areas could increase low flows. Activities such as cutting, filling, compacting, and paving of the land surface in and near areas of ground-water recharge could decrease low flows through reduced infiltration. Road cuts could also serve as potential ground-water loss areas affecting ground-water movement and storage (Parizek, 1971).

The increased low flows at station 16226200 that were significant after highway construction in comparison to during construction is partly related to the channelization of North Halawa Stream in the areas of streamflow loss or infiltration, as most of the channelization occurred in the areas of streamflow loss which is upstream of altitude 400 ft (Izuka, 1992). About 20 percent of the stream channel upstream of station 16226200 was channelized, which would reduce the streamflow loss to ground water and increase flows downstream. Additionally, areas of North Halawa Stream where there is streamflow gains also receive flow from highway runoff.

Low flows increased during and after construction at station 16270900 when compared to low flows before construction. Removal of vegetation during highway construction could have resulted in decreased evapotranspiration and hence an increase in the volume of

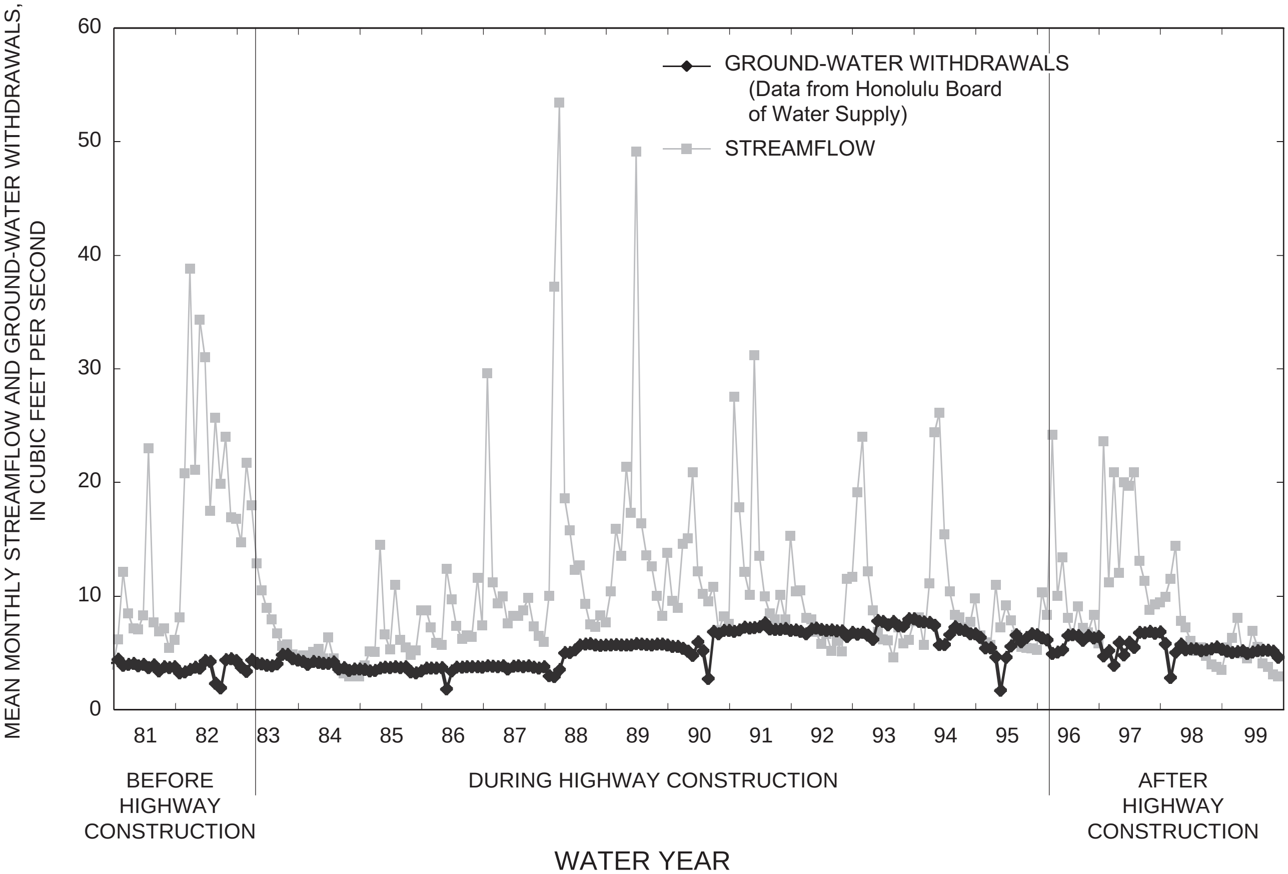


Figure 6. Mean monthly streamflow at streamflow-gaging station 16272200 and mean monthly upstream ground-water withdrawals, Oahu, Hawaii, water years 1981–99.

ground water available to maintain low flow. Hill (1996) determined that highway construction removed banana trees covering about 6 percent of the Luluku drainage basin. The effect of this vegetation removal in the drainage basin could potentially increase streamflow due to decreased evapotranspiration. Most likely reduced agricultural streamflow diversions for irrigation of the removed banana trees and highway runoff contribute to the increased low flows.

Low flows decreased at station 16272200 during highway construction in relation to low flows before construction. Upstream of station 16272200, the combined area affected by H-3 Highway and golf course construction was about 12 percent of the Kamooalii drainage basin area. Reduced evapotranspiration due to vegetation removal during construction would likely increase low flows, but low flows decreased during construction. The decrease in low flows indicates that the effects of increased ground-water withdrawals and compaction of soil during highway and golf-course construction (reduced infiltration) likely decreased the amount of water available to sustain low flows.

High and Peak Flows

In comparing the before and during highway-construction data, high flow increases were significant at only streamflow-gaging station 16275000 (tables 8 and 9). The increased high flows are probably the result of increased runoff from the clearing of vegetation and compaction (less infiltration) of areas used for highway construction. Only the increase in high flows at station 16272200 was significant in comparing the during and after periods of construction. The increased high flows at this station are probably the result of the same factors at station 16275000 and possibly the new golf course. Irrigation of the golf course could cause an increase in high flows due to higher soil moisture. Station 16270900 was the only station that had a significant

Table 11. Annual total suspended-sediment loads at sediment-gaging stations in the H-3 Highway study area, Oahu, Hawaii, water years 1981–99

[--, no data; shaded values represent data collected during periods of highway construction]

Water year	Annual total suspended-sediment load in tons						
	Station						
	16225800	16226200	16265600	16270900	16272200	16273950	16275000
1981	--	--	--	--	723	--	--
1982	--	--	--	--	3,210	--	--
1983	--	[1]5	[1]13	--	173	--	--
1984	--	31	24	[2]1	77	--	[3]6
1985	--	314	541	43	336	--	--
1986	--	362	472	91	322	--	--
1987	--	615	631	402	1,190	--	[4]114
1988	--	3,500	1,730	485	2,240	187	1,310
1989	--	16,600	1,220	180	1,290	488	3,400
1990	--	2,260	1,160	53	593	73	1,660
1991	[2]894	5,220	512	333	1,270	435	2,970
1992	3,650	4,290	65	70	148	82	1,610
1993	3,810	3,460	421	185	801	102	359
1994	2,180	9,180	278	193	606	182	665
1995	663	2,505	64	66	222	49	75
1996	267	5,040	1,940	884	1,370	57	683
1997	397	19,600	146	135	424	131	770
1998	286	2,780	--	[5]15	131	[5]25	87
1999	179	573	--	--	--	--	--

[1] Data from February to September

[2] Data from April to September

[3] Data from December to September

[4] Data from July to September

[5] Data from October to June

increase in high flows when comparing the before and after construction data. Station 16270900 also had a significant increase in peak flows as well. The increased high and peak flows here are most likely due to increased runoff from the highway.

SUSPENDED-SEDIMENT LOADS BEFORE, DURING, AND AFTER CONSTRUCTION

Annual suspended-sediment loads were low during 1983–86 (table 11) when rainfall and streamflow were low and loads were high during 1988–89, 1991, and 1996–97 when rainfall and streamflow were high and after construction had begun upstream of all sediment stations. The highest annual suspended-sediment load was at station 16226200 in 1997 (table 11), the last year of construction activities in North Halawa Valley.

Mean daily suspended-sediment yields were computed for before, during, and after construction periods by dividing mean daily suspended-sediment loads by drainage basin areas. Suspended-sediment yields were highest before construction at stream-gaging stations 16272200 and 16273950, highest during construction at stations 16225800, 16226200, 16265600, and 16275000, and highest after construction at station 16270900 (fig. 7). As noted previously, there were no before-construction data collected at stations 16225800 and 16265600.

Suspended-Sediment Load Changes due to Construction

The analysis of covariance procedure requires that the covariate, streamflow, be independent of the factor represented by the dummy variable, in this case, construction (Wildt and Ahtola, 1978). This assumption

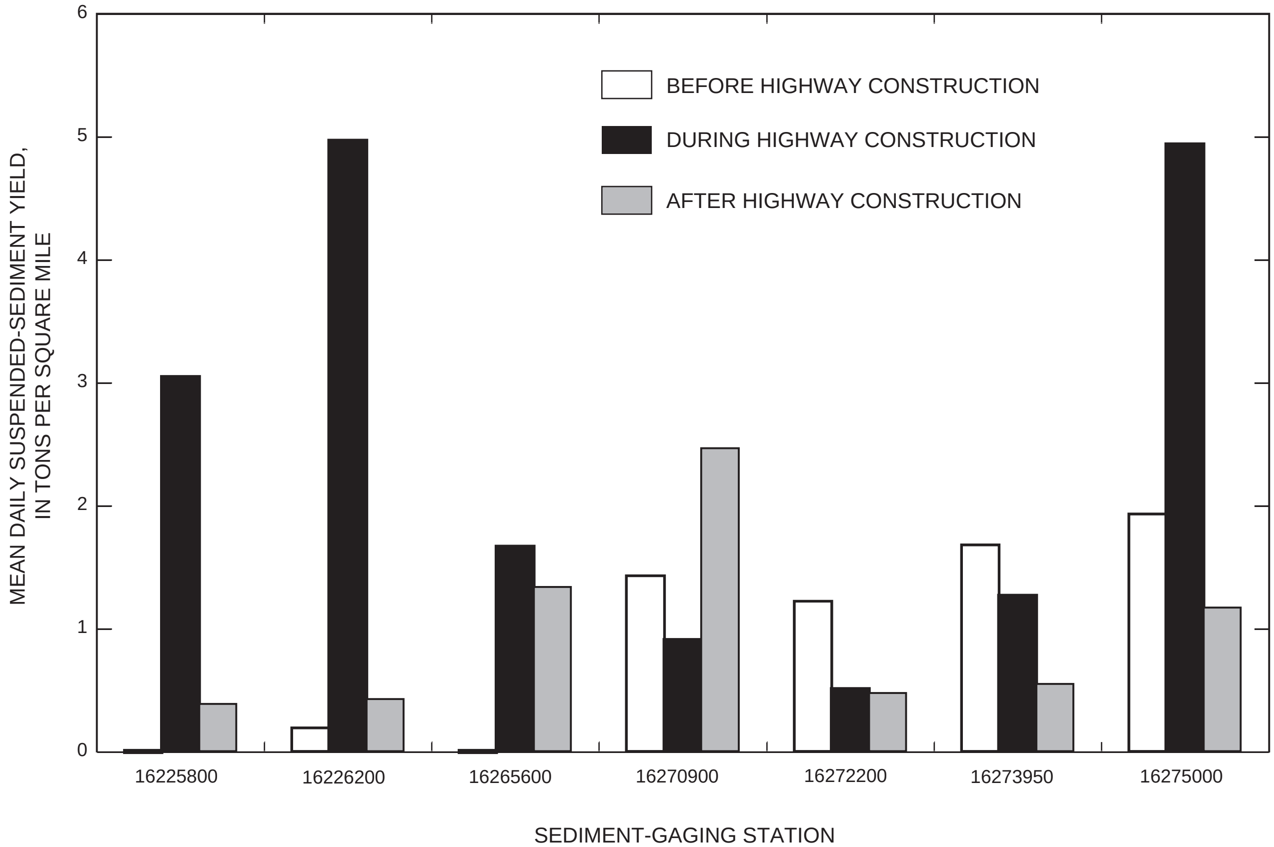


Figure 7. Mean daily suspended-sediment yield for the before, during, and after highway construction periods at sediment-gaging stations in the H-3 Highway study area, Oahu, Hawaii, water years 1981–99.

was checked by the analysis of covariance for high flows, since most sediment transport occurs during the period of high flows. The significant effects on high flows for the three analyses (before and during, during and after, and before and after highway-construction periods) determined at stations 16270900, 16272200, and 16275000 (tables 8 and 9) may affect the analysis of covariance results for suspended-sediment during the same highway-construction periods. However, this is unlikely as the data used in the tobit regression program were 500 randomly selected data points using suspended-sediment load data with both low and high flow data. The complete randomization of the data set helped to create independence between streamflow and the dummy variable, Z, as no linear correlation coefficient was higher than 0.46 in any tobit regression data set.

Before and during construction.--Analysis of covariance results indicate that relations between streamflow and suspended-sediment loads changed significantly at sediment-gaging stations 16226200, 16270900, 16272200, 16273950, and 16275000 (table 12; fig. 8). Changes in regression intercepts were significant at all stations except 16275000. The regression intercept increased during construction at stations 16226200, 16270900, and 16273950 and decreased at station 16272200 (table 12). Changes in regression slopes were significant at all stations except 16273950. Regression slopes increased during construction at stations 16226200, 16272200, and 16275000 and decreased at station 16270900.

During and after construction.--Relations between streamflow and suspended-sediment loads changed significantly after the highway-construction period for the during and after highway analysis of covariance at all sediment-gaging stations except 16275000 (table 12). Changes in regression intercepts were significant at all stations except 16275000. Regression intercepts increased at station 16273950 and decreased at the remaining stations. Changes in

Table 12. Analysis of covariance results relating randomly selected daily suspended-sediment loads to mean daily streamflow at sediment-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 likelihood ratio and F-statistics; * indicates significant effect of period on the basis of likelihood ratio or F-test; critical likelihood 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	Regression coefficients for				Likelihood ratio for significance of *Z*	F-statistic for significance of	
	Intercept	Slope	*Z*	*W*		*W*	*Z* + *W*
Before and during highway construction periods							
16226200	–1.97	0.368	0.978*	0.919*	119*	219*	144*
16270900	–1.75	2.74	0.247*	-0.830*	27.7*	23.8*	24.2*
16272200	–1.60	1.10	–0.573*	0.562*	10.6*	11.8*	6.43*
16273950	-2.06	2.98	0.141*	0.049	3.70*	1.00	15.5*
16275000	–2.63	3.08	–0.104	0.444*	1.19	5.49*	7.18*
During and after highway construction periods							
16225800	-0.824	1.39	-0.709*	0.128	67.9*	3.28	35.4*
16226200	-1.04	1.25	-0.708*	-0.385*	45.6*	19.7*	21.0*
16265600	-1.45	2.41	-0.689*	0.278	97.7*	2.02	53.7*
16270900	-1.51	1.82	-0.542*	1.37*	97.8*	26.6*	51.8*
16272200	-2.01	1.50	-0.403*	0.454*	9.42*	12.4*	6.85*
16273950	-2.03	3.33	0.286*	-0.819*	22.7*	25.0*	13.2*
16275000	-2.54	3.45	-0.111	0.244	1.37	1.95	1.95
Before and after highway construction periods							
16226200	–2.08	0.287	0.471*	0.718*	27.3*	85.6*	43.4*
16270900	–1.82	2.74	-0.368*	0.890*	31.0*	19.0*	21.2*
16272200	–1.80	1.30	–0.379*	0.348*	12.8*	12.1*	7.60*
16273950	-2.10	2.92	0.380*	-0.522*	39.6*	13.1*	48.2*
16275000	–2.80	3.46	0.232*	-0.188	6.37*	1.04	5.17*

regression slopes were significant at stations 16226200, 16270900, 16272200, and 16273950. Regression slopes increased after construction at stations 16270900 and 16272200 and decreased at stations 16226200 and 16273950.

Before and after construction.--Analysis of covariance results indicate that relations between streamflow and suspended-sediment loads for the before and after highway-construction periods changed significantly at sediment-gaging stations 16226200, 16270900, 16272200, 16273950, and 16275000 (table 12). Intercept changes were significant at all stations. Regression intercepts increased at stations 16226200, 16273950, and 16275000 and decreased at stations 16270900 and 16272200 (table 12). Changes in regression slopes were significant at all stations except 16275000. Regression slopes increased at stations 16226200, 16270900, and 16272200 and decreased at station 16273950.

Streamflow and suspended-sediment load relations.--Changes in regression coefficients indicate how streamflow-sediment relations were affected during the highway-construction periods compared. Changes in regression slopes and intercepts reflect changes in the availability of suspended sediment. Figure 8 graphically illustrates the changes in slope and intercept of tobit regression lines in table 12. The significant decrease in intercept at station 16225800 after construction, and the lack of significant change in slope, indicate that suspended-sediment loads decreased relative to streamflow after construction (table 12, fig. 8). This decrease affected the entire range of streamflow at this station as would be expected once land disturbances from highway-construction stopped. At station 16226200, the increase in slope and intercept during construction compared to before construction indicate that suspended-sediment loads increased relative to streamflow during construction (table 12, fig. 8). As a result of the increase

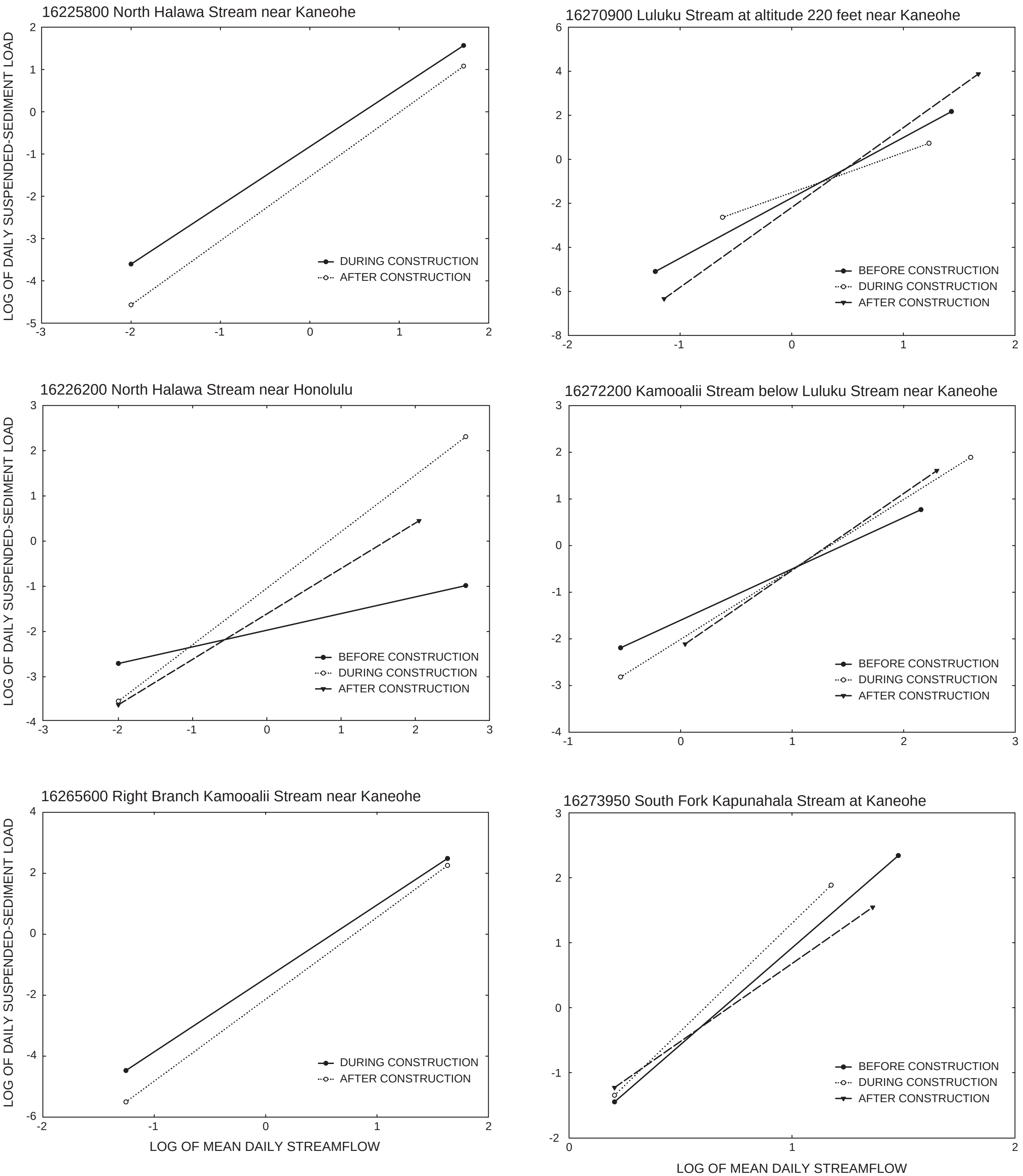


Figure 8. Before, during, and after highway-construction period relations between streamflow and suspended-sediment loads at streamflow- and sediment-gaging stations in the H-3 Highway study area, Oahu, Hawaii.

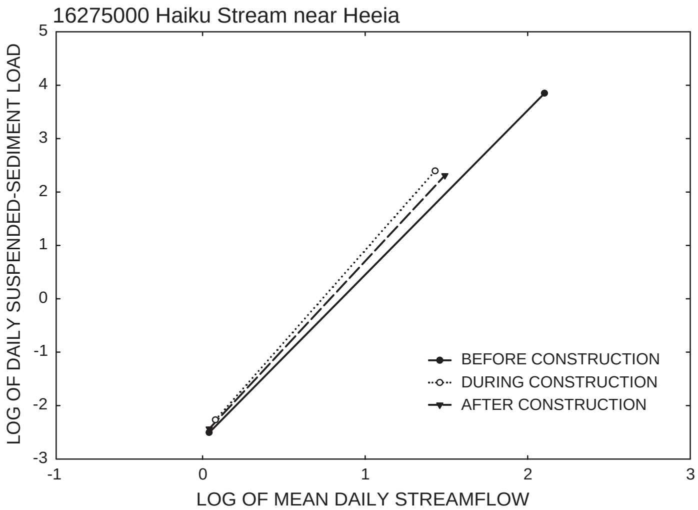


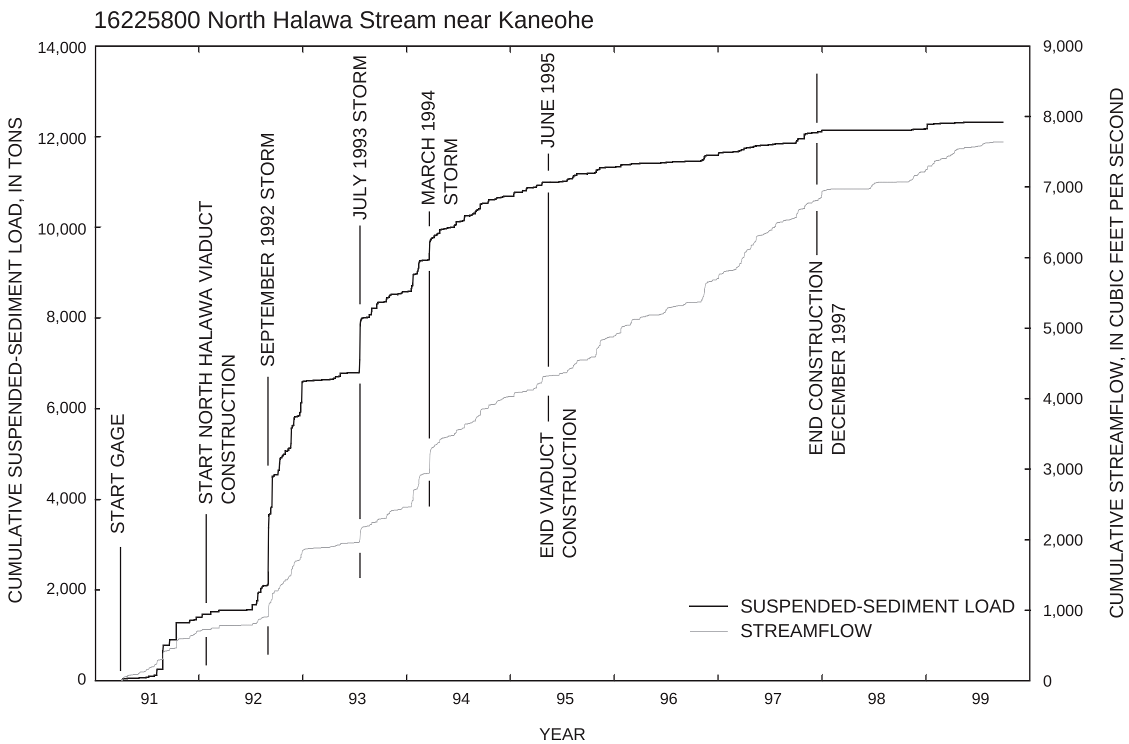
Figure 8. Before, during, and after highway-construction period relations between streamflow and suspended-sediment loads at streamflow- and sediment-gaging stations in the H-3 Highway study area, Oahu, Hawaii--Continued.

in slope, the construction regression line is actually below the before construction regression line for flows less than 0.08 ft^3/s. Because 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. The slope and intercept decreased after construction when compared to during-construction data at station 16226200, which indicates decreased suspended-sediment loads relative to streamflow after construction. The slope of the after-construction relationship line is higher than the before construction line and the two lines intersect at about 0.27 ft^3/s. Again, at such low flows very little sediment is transported so the intersection of the regression lines is not significant in assessing the effects of construction on sediment loads. For stations 16225800 and 16226200, the differences in slope of cumulative suspended-sediment loads and streamflow between the before, during, and after highway-construction periods can clearly be seen (fig. 9). Additionally, figure 9 shows the large increases in suspended-sediment loads that are generated by storms especially for the during highway-construction period. The cumulative suspended-sediment load graphs for 16225800 and 16226200 also show that from April 1991 to September 1999, 12,300 tons of suspended sediment passed station 16225800. For that same time period, 48,800 tons of suspended sediment passed station 16226200. Thus, from April 1991 to September 1999, station 16225800, with 41 percent of the drainage area of station 16226200, contributed 25 percent of the suspended-sediment load at station 16226200.

At sediment station 16265600, the analysis of covariance intercept decreased and slope increased after construction than during construction. However, the change in slope was not significant. The plot of the tobit regression lines (fig. 8) indicates a decrease in suspended-sediment load over the entire range of streamflow. Excluding the January 1996 storm, the cumulative suspended-sediment load graph (fig. 9) shows a lower slope in the cumulative totals after construction than during construction.

At sediment-gaging station 16270900, the analysis of covariance slope decreased and intercept increased (fig. 8) during construction in comparison to the before-construction data. The before- and during-construction regression lines intersect at about 1.8 ft^3/s. Suspended-sediment loads are estimated to be higher before construction for streamflows above 1.8 ft^3/s and higher during construction for streamflows lower than 1.8 ft^3/s. After construction the slope increased and intercept decreased compared to both the before and during construction time periods (table 12, fig. 8). Streamflows higher than about 3.1 ft^3/s had a higher suspended-sediment load after construction than streamflows higher than 3.1 ft^3/s before construction. The same is true for streamflow above 2.4 ft^3/s after construction than during construction. The differences in slope are not as clearly seen in the cumulative suspended-sediment load graph (fig. 9) between the time periods compared, however, the curve does show larger increases before and after construction than during construction.

At sediment-gaging station 16272200, the analysis of covariance slope increased and intercept decreased in all three comparisons (fig. 8). The intersection point of the regression lines was about 11, 16, and 11 ft^3/s for the before and during, during and after, and before and after highway-construction period comparisons, respectively. Thus, suspended-sediment loads in relation to high streamflow increased both during and after construction than before construction. For lower streamflows, suspended-sediment loads were higher in the before construction period than either during or after construction. This can be seen in the lower mean daily suspended-sediment yields for this station for the during and after highway construction periods compared to the



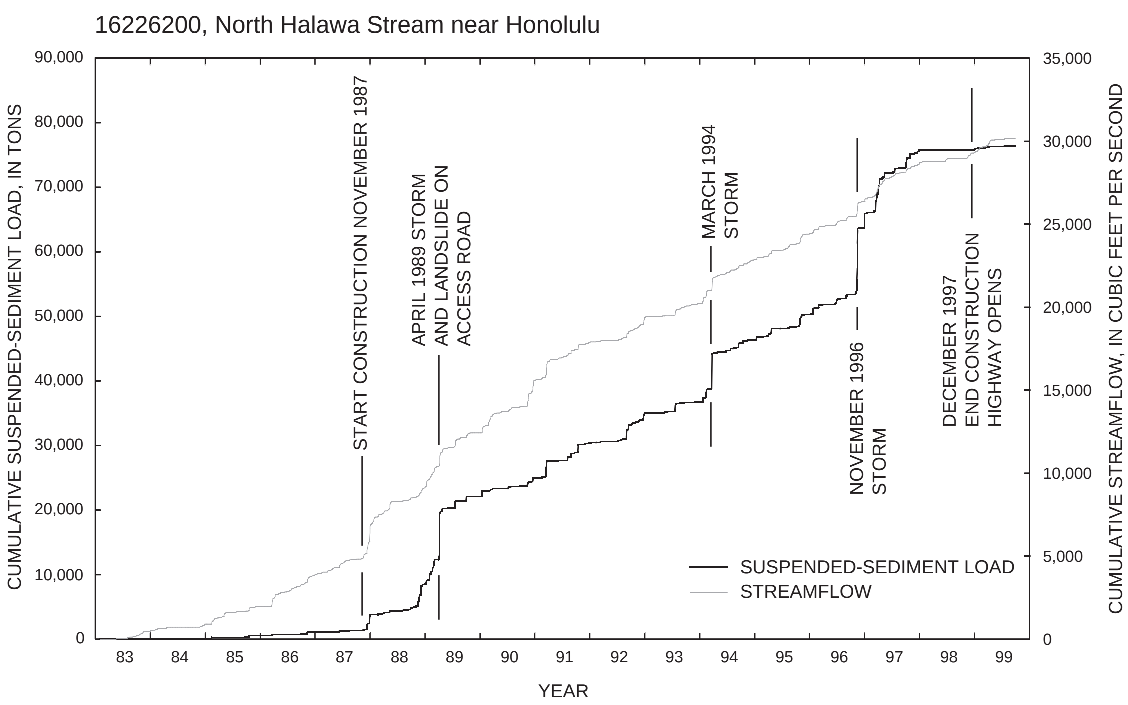
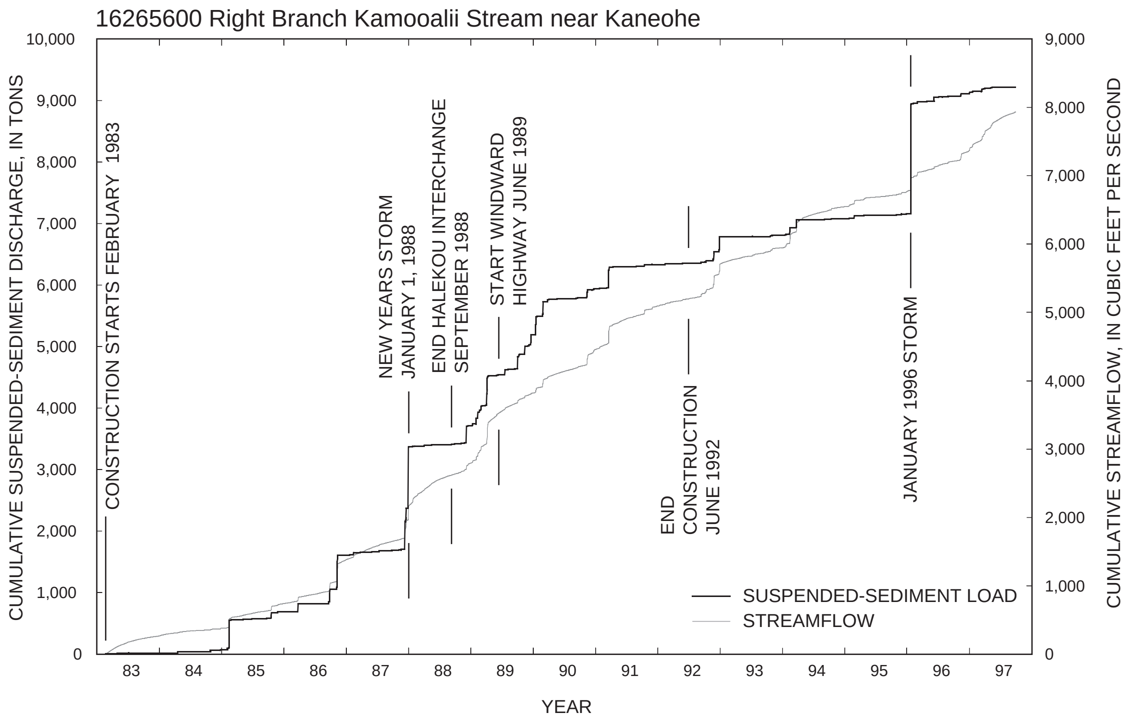


Figure 9. Cumulative streamflow and suspended-sediment loads at streamflow and sediment-gaging stations in the H-3 Highway study area, Oahu, Hawaii, 1981–99.



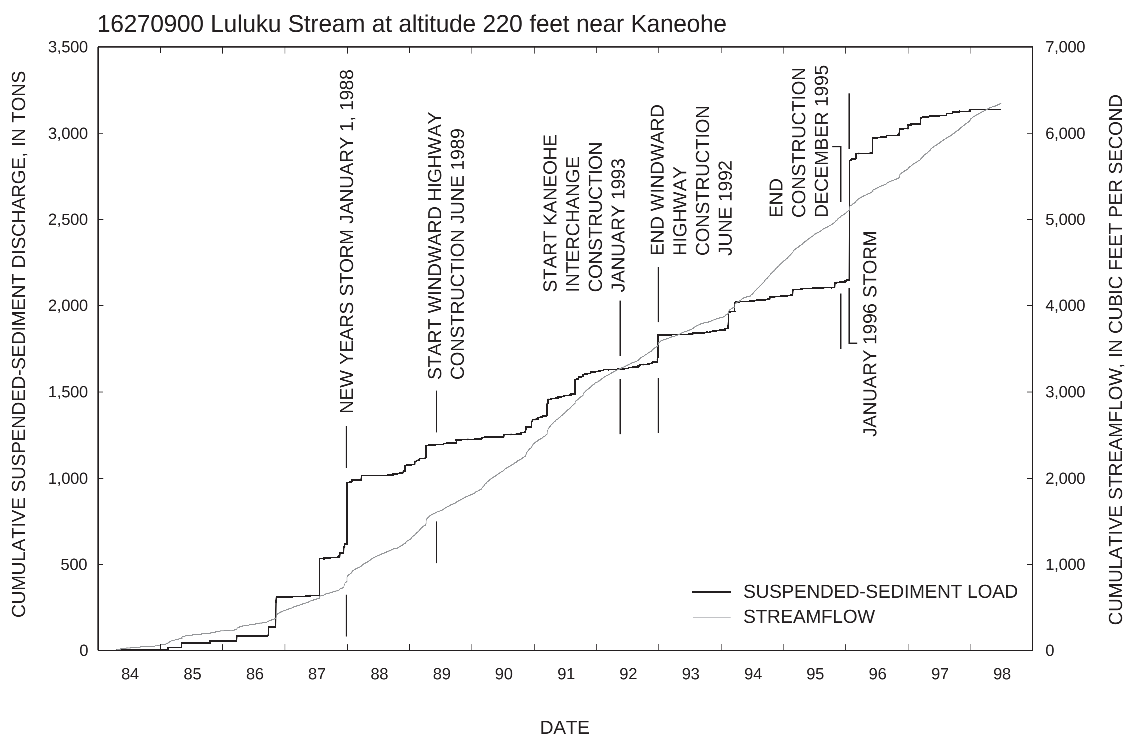


Figure 9. Cumulative streamflow and suspended-sediment loads at streamflow and sediment-gaging stations in the H-3 Highway study area, Oahu, Hawaii, 1981–99--*Continued*.

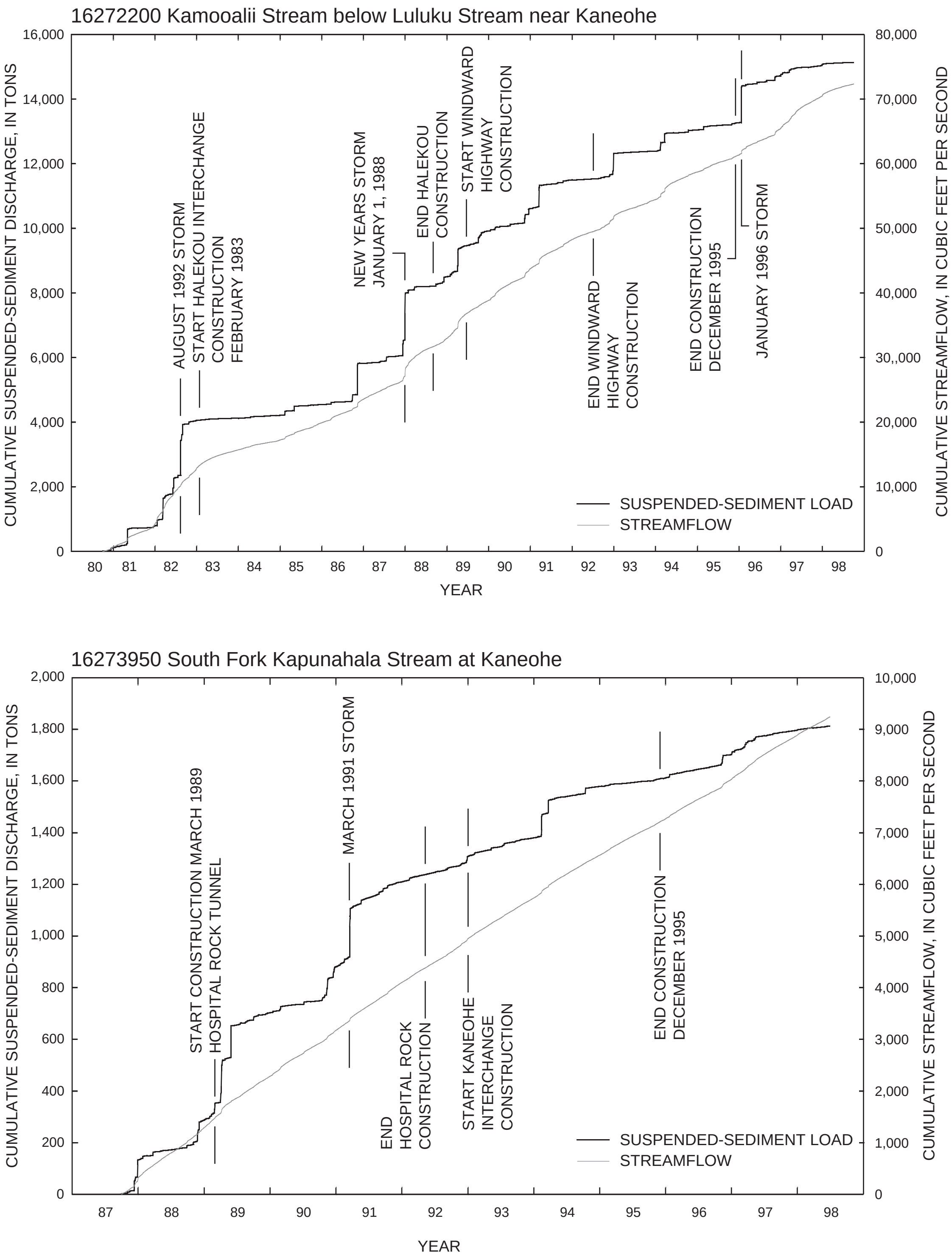


Figure 9. Cumulative streamflow and suspended-sediment loads at streamflow and sediment-gaging stations in the H-3 Highway study area, Oahu, Hawaii, 1981–99--*Continued*.

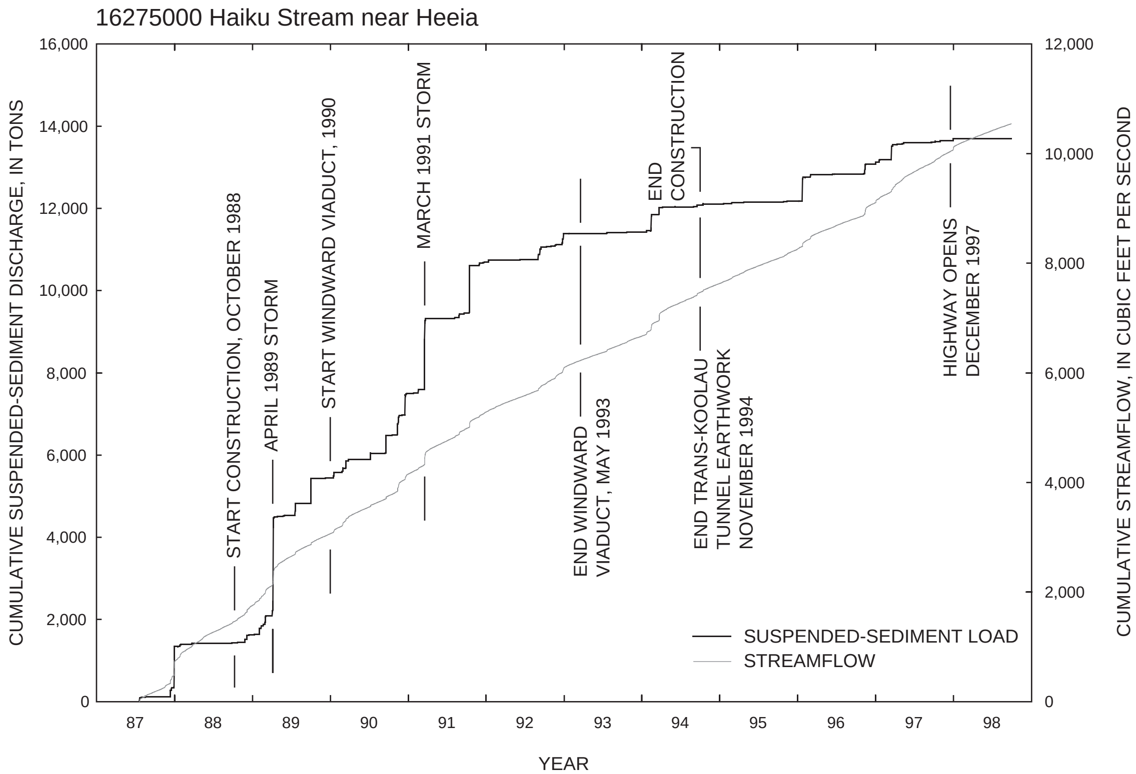


Figure 9. Cumulative streamflow and suspended-sediment loads at streamflow and sediment-gaging stations in the H-3 Highway study area, Oahu, Hawaii, 1981–99--Continued.

before (fig. 7). The slope of the cumulative suspended-sediment load graph for station 16272200 (fig. 9) shows a steeper slope only during the construction of the Windward Highway segment of H-3 Highway and not the earlier Halekou Interchange construction which shows a flatter slope similar to the before and after construction time periods. The cumulative suspended-sediment load graph for stations 16270900 and 16272200 (fig. 9) indicates that station 16270900, with 11 percent of the drainage area, contributed 29 percent of the suspended-sediment load to station 16272200 during April 1984 to June 1998. The remaining suspended-sediment load at station 16272200 was that which had passed through the reservoir upstream of the station.

At sediment station 16273950, the analysis of covariance slope and intercept increased during highway construction when compared to the before construction relation. The increase in slope was not significant, however. The tobit regression line (fig. 8) does shows an increase in suspended-sediment load over the entire range of streamflow. The slope decreased and intercept increased after construction when compared to both during and before construction data. The suspended-sediment load decreased for all streamflows except for flows below 2.1 ft^3/s after construction when compared to during construction. The suspended-sediment load decreased in relation to streamflow after construction compared to before construction data for streamflows greater than about 4 ft^3/s. The cumulative suspended-sediment load graph (fig. 9) shows a near constant slope throughout the study period with a slightly lower slope only in the after construction period.

At sediment-gaging station 16275000, the analysis of covariance slope increased and intercept decreased during highway construction when compared to before construction data. The decrease in intercept was not significant, however. The increase in slope did however, affect the entire range of streamflow (fig. 8). Neither slope nor intercept were significant in comparing the during and after construction data. Figure 8 shows that the after-construction relation has a lower suspended-sediment load throughout the entire range of streamflow compared to the during-construction regression line, but is still higher than the before construction relation. This is because only the increase in intercept was significant in the comparison of the before and after construction data. The cumulative suspended-sediment load graph (fig. 9) shows a steeper slope during the construction period than in either the before or after time periods.

The before and during highway-construction period regression equations cannot be used to estimate construction effects on suspended-sediment loads similar to streamflows because of limitations of the statistical techniques used. Limitations at stations 16226200, 16272200, and 16275000, were that the range of streamflow data during construction exceeds the range of streamflow before construction. Extrapolation beyond the range of data used to develop the regression equations 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 the appropriate regression relations or bias-correction factors (Cohn, 1988; Helsel and Hirsch, 1992). Instead, regional sediment-transport relations determined by Hill (1996) were used to estimate the construction effects.

Effects of Land-Use Changes on Suspended-Sediment Loads

Hill (1996) derived two equations useful for estimating the annual suspended-sediment yields expected in the absence of construction effects or other major land-use changes. Using annual suspended-sediment yields reported for other areas of Oahu and before-construction suspended-sediment yields at H-3 study stream-gaging stations, Hill (1996) used regression analysis with annual water yield (streamflow per unit area) to derive the two equations.

The first equation for estimating the annual suspended-sediment yields is based on data from drainage basins in the leeward Koolau Range and the before highway-construction period data from station 16226200 and was used to estimate the suspended-sediment yields expected at stations 16225800 and 16226200 during and after the construction period without the effects of highway construction. Data used to derive equation 6 was transformed to common logarithms to obtain a more linear relation, and was expressed as:

$$\log S_y = -2.91 + (1.96 \times \log Q_y), \qquad (6)$$

where S_y represented annual suspended-sediment yield and Q_y represented annual water yield. A total of 18 annual suspended-sediment yields were used to compute the regression, which had a coefficient of determination of 86 percent and a standard error of 0.22 log units. A bias-correction factor of 1.15 was applied to correct for re-transformation error (Duan, 1983) when applying the equation to stations 16225800 and 16226200.

The second equation for estimating the annual suspended-sediment yields is based on data from windward Oahu stations and the before highway-construction data from stations 16265600, 16270900, and 16275000, with no log-transformation needed. Hill (1996) did not use the before-construction data at station 16273950 as the suspended-sediment loads were not computed at that time. The addition of this one annual yield (water year 1988) would not significantly change the equation. This equation was expressed as:

$$S_y = 30 + (0.529 \times Q_y). \qquad (7)$$

Equation 7 was based on 14 measured suspended-sediment yields and had a coefficient of determination of 56 percent with a standard error of 336 tons/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. Suspended-sediment yields at station 16272200 cannot be estimated by strictly using equation 6 because the reservoir upstream of the station traps sediment and reduces the yield at the station. Estimated yields at station 16272200 were determined in part using data from Wong (2001) and is explained in the following section.

Annual suspended-sediment yields expected in the absence of highway construction effects were estimated by applying regression equations 6 and 7 with the adjustment factors described in the next paragraph to construction-period annual water yields. The annual suspended-sediment yields were then summed for the construction period and compared to the total observed suspended-sediment yields for the construction-period at each station. The estimated yields were subtracted from the observed yields and the resulting differences represented the increase or decrease in yields attributable to highway construction. The percent change was computed using equation 5 with *OBS* equal to the observed suspended-sediment yield and *EST* equal to the estimated yield. The percent change represents the percent of the estimated suspended-sediment yield attributed to highway construction and are presented in table 13. The after-construction estimates of suspended-sediment yields were computed and compared in the same way except the after-construction annual water yields were used in equations 6 and 7. The after-construction estimates of suspended-sediment yields are not dependent on either a during and after or a before and after construction comparison.

To determine how well equations 6 and 7 would work for estimating suspended-sediment yield changes due to highway construction, results from both equations were compared to the observed before highway-construction data. The percent differences from this comparison (table 13) were then used to create adjustment factors to better fit the estimated yields to the observed yields. These adjustment factors are a constant that is multiplied against the estimated yields from equations 6 and 7 to provide a better estimate of suspended-sediment yields then equations 6 and 7 alone. Excluding the -57 percent difference at station 16273950 (table 13) as not being representative of the other stations, the average absolute value percent difference was 26 percent. This value was used as the accuracy of equations 6 and 7. Along with the 15 percent accuracy of the suspended-sediment records, a combined accuracy of 30 percent was computed. The 30 percent accuracy was computed as the square root of the sum of squares of each accuracy value (Benjamin and Cornell, 1970; Rabinovich, 1995). Thus, only those percent differences greater than 30 percent can be considered hydrologically significant.

Differences in annual suspended-sediment yields during highway construction ranged from a decrease of 3,460 tons/mi^2 (-62 percent) of the observed suspended-sediment yield at station 16270900, to an increase of 14,900 tons/mi^2 (426 percent) of the observed yield at station 16226200 (table 13). The increased yields at stations 16225800, 16226200, 16265600, and 16275000 were all significant at 222, 426, 60, and 148 percent, respectively. At stations 16270900 and 16273950, the suspended-sediment yield significantly decreased during construction by 62 and 37 percent. The decrease of 16 percent at station 16272200 was not significant. Therefore, increased suspended-sediment yields resulting from construction activities ranged from 60 to 426 percent higher than before construction yields where significant increases in suspended-sediment loads were detected (table 12). At sediment-gaging stations 16225800 and 16265600, the during construction increases in suspended-sediment yields were probably also statistically significant although this could not be tested due to no before-construction data. This is because the during and after construction analysis of streamflow and suspended-sediment load was statistically significant and that all the stations tested in the before and during construction analysis had statistically significant changes in the streamflow and suspended-sediment load relations.

Differences in suspended-sediment yields after highway construction ranged from a decrease of 1,410 tons/mi^2 (-62 percent) at station 16272200 to an increase of 680 tons/mi^2 (36 percent) at station 16265600 (table 13). Highest percent difference was at station 16226200 with 205 percent. Observed after-construction suspended-sediment yields were significantly higher at stations 16225800, 16262200, and 16265600, with percent increases of 49, 205, and 36, respectively. Observed yields were lower at stations 16272200 and 16273950 with percent differences of -62 and -71 percent. Estimated increases in suspended-sediment yield after construction are most likely due to drainage basins still adjusting to the effects of highway construction. It may be a few more years before after-construction yields return to levels estimated if no land-use change has occurred (before construction). The cumulative suspended-sediment graphs (fig. 9) show lower slopes in most cases after construction than during which signifies a decrease in suspended-sediment loads after construction. This is also seen in the mean daily suspended-sediment values shown in figure 7. At stations where increases were estimated after construction (table 13), these increases were lower than the

Table 13. Estimated changes in suspended-sediment yields at sediment-gaging stations for the before, during, and after highway-construction periods in the H-3 Highway study area, Oahu, Hawaii,1983–99

[Estimated suspended-sediment yields were computed from regression equations (Hill, 1996, p. 29) relating annual suspended-sediment yields to annual streamflow per unit area and the computed adjustment factor; data used for stations 16225800 and 16226200 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; observed and estimated yields at station 16272200 were adjusted due to the upstream reservoir; yields from regression equations were then multiplied by the adjustment factors listed to get estimated yields, adjustment factors were computed from the before construction percent difference; 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 estimated yields and multiplied by 100; *, indicates significant hydrologic effect because the difference is greater than 30 percent; --, not applicable]

Station	Suspended-sediment yields (tons/mi^2)		Difference between observed and estimated yields		Computed adjustment factor	Adjustment factor used in estimating yields
	Observed	Estimated	(tons/mi^2)	(percent)		
Before highway construction						
16226200	322	422	–100	–24	0.806	--
16270900	2,710	2,120	590	28	1.28	--
16273950	879	2,040	–1,160	–57	0.637	--
16275000	1,480	1,170	310	26	1.26	--
During highway construction						
16225800	7,230	2,240	4,990	222*	--	0.806
16226200	18,400	3,500	14,900	426*	--	0.806
16265600	5,720	3,580	2,140	60*	--	1.28
16270900	2,150	5,610	–3,460	–62*	--	1.28
16272200	7,560	9,000	–1,440	–16	--	1.28
16273950	3,140	4,990	–1,850	–37*	--	0.637
16275000	11,000	4,440	6,560	148*	--	1.26
After highway construction						
16225800	284	191	93	49*	--	0.806
16226200	284	93	191	205*	--	0.806
16265600	2,580	1,900	680	36*	--	1.28
16270900	2,270	2,100	170	8	--	1.28
16272200	870	2,280	–1,410	–62*	--	1.28
16273950	505	1,740	–1,240	–71*	--	0.637
16275000	1,630	2,190	–560	–26	--	1.26

increases during construction. The 26 percent decrease at station 16275000 and 8 percent increase at station 16270900 are within the 30 percent criteria of accuracy and shows that suspended-sediment loads have returned to before-construction levels at these two stations.

The negative difference for station 16270900 during construction (table 13) indicates that suspended-sediment yields during construction would have been higher under before-construction conditions than during-construction conditions. Before construction, most of the drainage basin upstream of station 16270900 was under banana cultivation. There have been no studies on sediment yields from banana plantations in Hawaii, but 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. Before-construction suspended-sediment yields at station 16270900 appear to be higher than yields for other windward drainage basins under mixed use (Hill, 1996). 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. Tobit regression results discussed previously also showed a decrease in sediment during construction (table 12, fig. 8).

The negative difference after highway construction at station 16273950 is more difficult to explain since banana cultivation in the basin was much smaller and the highway construction removed only a few small agricultural and rural housing plots near the sediment-gaging station. Tobit regression results also showed that suspended-sediment loads in relation to streamflow increased during construction at station 16273950 (fig. 8). The highway construction may have reduced the suspended-sediment yield in this drainage basin by diverting runoff and trapping sediment; the portion of H-3 is entirely on grade and bisects the upper quarter of the drainage basin (fig. 2). This could have the effect of trapping sediment (also reducing runoff) from these areas which include some banana acreage but mostly undeveloped land upstream of the highway. Also, the stormwater runoff channels were changed during construction resulting in runoff from the Likelike Highway that used to enter the stream upstream of station 16273950 to enter downstream of the station after highway construction. However, changes in low- and highflows at station 16273950 were not hydrologically significant (table 10).

The suspended-sediment yield at station 16272200 is affected by the Waimaluhia Reservoir. Suspended-sediment yield to the reservoir was determined to be 8,420 tons/mi^2 from 1983 to 1998 (Wong, 2001). This sediment yield can be divided into 7,560 tons/mi^2 during construction from 1983 to 1995 and 870 tons/mi^2 after construction from 1995 to 1998. Inflow to the reservoir can be computed by a simple water budget relation in which outflows equals inflows. Because groundwater seepage from the reservoir was negligible and the seepage that was observed flowed into the stream upstream of station 16272200, and because rainfall on the reservoir (75 in/yr) exceeded the evaporation from the reservoir (less than 50 in/yr), the flow measured at station 16272200 minus the flow at station 16270900, a tributary to 16272200 that does not flow into the reservoir, equals the reservoir outflow and thus inflow to the reservoir (Wong, 2001). Annual streamflow yields were then computed from the annual inflows with estimates for water years 1984 and 1998 to account for the partial years of record at station 16270900. Equation 7 was applied to these annual water yields with a 1.28 adjustment factor, which was computed for use at stations 16265600 and 16270900, applied. The total suspended-sediment yield to the reservoir was 9,000 tons/mi^2 for water years 1984 to 1995. The difference is -1,440 tons/mi^2 from the observed sediment yield which is an decrease of 16 percent during construction. Equation 7 only estimates the suspended-sediment yield and not the total sediment yield which was computed for the reservoir. The total sediment yield includes larger sediment particles such as cobbles and boulders which are moved during larger storms as bedload transport. Therefore, the use of equation 7 in this case will only provide a rough guide to the effects of the highway construction on the suspended-sediment yield to the reservoir and station 16272200. The 16 percent difference is, however, within the accuracy range of the suspended-sediment records so even though the tobit regression analysis indicated an increase in suspended-sediment load for higher streamflows at station 16272200, the estimated magnitude of that increase is not significant. The estimated suspended-sediment yield after construction to the reservoir was computed as 2,280 tons which is 1,410 tons greater than that observed for a decrease of 62 percent. The decrease is most likely due to the effects of the highway and golf course construction reducing the natural sediment load. The H-3 Highway in the Kamooalii Stream basin bisects the upper and lower portions of the drainage basin (fig. 2) and may act as a sediment trap to the undeveloped land upstream of the highway. The decrease may also be due the decreased suspended-sediment yields during construction at station 16270900, a tributary to station 16272200, not affected by the reservoir.

COMPARISON WITH PREVIOUS STUDIES

The additional streamflow and suspended-sediment load data after 1991 in the before and during highway construction analysis, did not change the low-flow results determined by Hill (1996). As in Hill (1996), both the significant low-flow increase at station 16270900 and decrease at station 16272200 were determined. The high flow results, however, did change. Where Hill (1996) found no significant changes in highflows during construction, it was determined that highflows increased at station 16275000 by 25 percent compared to before construction. The suspended-sediment load changes at stations 16226200, 16265600, 16270900, 16272200, and 16275000 repeated those determined by Hill (1996). Percent increases were higher than those computed by Hill (1996) at stations 16226200, 16265600, and 16275000 and the percent decrease was not as low at station 16270900. No change in load was also determined at station 16272200.

The high flow increases determined at stations 16270900 and 16272200 after construction and at station 16275000 during construction cannot be readily

Table 14. Estimated changes in observed suspended-sediment yields due to highway construction at sediment-gaging stations for the during and after highway-construction periods in the H-3 Highway study area, Oahu, Hawaii,1983–99

[Estimated suspended-sediment yields were computed from regression equations (Hill, 1996, p. 29) relating annual suspended-sediment yields to annual streamflow per unit area and the computed adjustment factor; data used for stations 16225800 and 16226200 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; observed and estimated yields at station 16272200 were adjusted due to the upstream reservoir; yields from regression equations were then multiplied by the adjustment factors listed to get estimated yields, adjustment factors were computed from the before construction percent difference; 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; *, indicates significant hydrologic effect because the difference is greater than 30 percent]

Station	Suspended-sediment yields (tons/mi^2)		Adjustment factor used in estimating yields	Difference between observed and estimated yields	
	Observed	Estimated		(tons/mi^2)	(percent of observed)
During highway construction					
16225800	7,230	2,240	0.806	4,990	69*
16226200	18,400	3,500	0.806	14,900	81*
16265600	5,720	3,580	1.28	2,140	37*
16270900	2,150	5,610	1.28	–3,460	–161*
16272200	7,560	9,000	1.28	–1,440	–19
16273950	3,140	4,990	0.637	–1,850	–59*
16275000	11,000	4,440	1.26	6,560	60*
After highway construction					
16225800	284	191	0.806	93	33*
16226200	284	93	0.806	191	67*
16265600	2,580	1,900	1.28	680	26
16270900	2,270	2,100	1.28	170	8
16272200	870	2,280	1.28	–1,410	–162*
16273950	505	1,740	0.637	–1,240	–245*
16275000	1,630	2,190	1.26	–560	–34*

compared to studies dealing with logging road impacts because of the larger drainage basin sizes of stations 16272200 and 16275000. Logging road effects were analyzed in basins less than 0.57 mi^2 (Harr and others, 1975; Ziemer, 1981; and King and Tennyson, 1984) while the areas at stations 16272200 and 16275000 are 3.81 and 0.99 mi^2 (table 1). The percentages of the drainage areas affected by highway construction are 5, 4, and 3 percent at stations 16270900, 16272200, and 16275000, respectively, which are similar to the 4 percent area affected needed to detect significant high flow effects in King and Tennyson (1984). The only significant peak flow increase was determined at station 16270900. Highway construction affected only about 5 percent of the drainage basin which is less than the 12 percent threshold for detecting increased peak flows due to logging road construction in forested areas (Harr and others, 1975).

Previous studies that have evaluated sediment loads due to highway construction in small drainage basins, have discussed the effect of the construction in terms of sediment load attributed to the construction and not a percentage increase or decrease (Vice and others, 1969; Eckhardt, 1976; Reed, 1980; Ward and Appel, 1988). To compare the results of this study to the other studies, it is necessary to compute the percent differences between the observed and estimated suspended-sediment yields or loads by equation 8. Equation 8 represents the percent change of the observed during- or after-construction suspended-sediment yields attributed to construction.

$$\text{Percent difference} = [(OBS - EST)/\,OBS] \times 100 \qquad (8)$$

Where *OBS* represents the observed suspended-sediment yield and *EST* the estimated yield. Note that percentages greater than -100 percent are the result of the computation method of equation 8 and not a reduction in suspended-sediment yield by an impossible amount. Percentages of the observed suspended-sediment yield that can be attributed to highway construction range from -161 to 81 percent during highway construction and from -245 to 67 percent after highway construction (table 14). Where suspended-sediment yields have increased due to construction, 37 to 81 percent of the observed yields are due to highway construction. This range is similar to the 50 to 85 percent range from previous studies in the eastern United States. The percentages of the after construction observed yields due to construction are smaller, ranging from 8 to 67 percent, indicating a reduced effect of highway construction on the suspended-sediment yields.

CONCLUSIONS

Analysis of covariance and regression techniques were used to assess the effects of the H-3 Highway construction on streamflow and suspended-sediment loads in the affected drainage basins during the time periods: before and during construction, during and after construction, and before and after construction. Results of the streamflow analyses indicated that low flows before and during construction changed significantly at two stream-gaging stations. Low flows increased 108 percent at station 16270900 and decreased 31 percent at station 16272200 during construction. Low flows after construction changed significantly only at station 16226200, increasing by 47 percent compared to low flows during the construction period. Low flows after construction compared to those before construction changed significantly only at station 16270900, increasing by 99 percent. Decreases in low flows at station 16272200 were probably caused by land-use changes due to highway construction and by increased groundwater withdrawals which occurred during the construction period. Increased low flows at stations 16226200 and 16270900 were attributed to highway construction.

High flows, mean daily streamflows over 10 ft^3/s at index stream-gaging station 16229000, changed significantly only at station 16275000, increasing 25 percent during highway construction compared to before construction. High flows after construction changed significantly only at station 16272200 by an increase of 34 percent compared to the high flows during construction. Relations between before and after construction high flows changed significantly only at station 16270900, increasing by 58 percent. All increases in high flows were attributed to land-use changes caused by highway construction. Increased runoff due to a new golf course built during the construction period upstream of station 16272200 may have also contributed to the increase in high flows observed at station 16272200. Highway construction affected about 5, 4, and 3 percent of the drainage areas at stations 16270900, 16272200, and 16275000, respectively. These values are similar to the 4 percent of the drainage area affected needed to detect significant high flow effects of logging road construction in the Pacific Northwest region of the continental United States.

Instantaneous peak flows were analyzed at only three stations, 16226000, 16270900, and 16275000, due to the limited amount of peak flow data at most gaging stations in the study area. Peak flows increased during and after construction only at station 16270900. The increase in peak flows at this station was attributed to land-use changes caused by highway construction which affected about 5 percent of the drainage area.

Suspended-sediment loads changed significantly at stations 16226200, 16270900, and 16275000 during highway construction compared to before highway construction. Suspended-sediment loads increased at stations 16226200 and 16275000 by 426 and 148 percent and decreased at station 16270900 by 62 percent. Suspended-sediment loads also increased during construction at stations 16225800 and 16265600, by 222 and 60 percent, but these changes could not be tested statistically since no before construction data were collected at these sites. All changes in suspended-sediment loads are attributed to highway construction. Increased loads are due to the land disturbance caused by the highway construction and the decreased loads due to other land-use changes such as a decrease in agricultural activities as well as erosion control measures installed during highway construction.

After highway construction, suspended-sediment loads changed significantly compared to during construction loads at all stations except 16275000. Suspended-sediment loads increased at stations 16225800, 16226200, and 16265600 by 49, 205, and 36 percent, respectively, and decreased at stations 16272200 and 16273950 by 62 and 71 percent. The percentage increases were lower than the increases computed for the during construction period indicating that the suspended-sediment loads are slowly returning to the before construction levels which has already been observed at stations 16270900 and 16275000. Decreased loads at station 16272200 are due in part to the upstream Waimaluhia Reservoir trapping sediment and the decrease of suspended-sediment loads at station 16270900. The decrease after construction at station 16273950 is due to highway construction reducing the amount of sediment available for transport in the South Fork Kapunahala Stream drainage basin.

Effects of H-3 Highway construction on suspended-sediment loads were generally similar to effects of highway construction in other areas. Previous studies in other areas of the United States found that 50 to 85 percent of the sediment loads were attributable to highway construction activities. Effects of H-3 Highway construction on suspended-sediment loads at stations 16225800, 16226200, 16265600, and 16275000 appear to be comparable to effects of highway construction in the eastern United States with 37 to 81 percent of the observed suspended-sediment load due to highway construction. Decreases in suspended-sediment loads due to highway construction are unique and have not been widely reported in the literature. Where decrease in suspended-sediment loads were determined, land use prior to construction was not pristine.

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Appendix 1. --Daily mean sediment discharge (tons/day) for water year 1996 at sediment-gaging station 16265600, Right Branch of Kamooalii Stream near Kaneohe, Oahu, Hawaii
[all daily values are estimated]

Day	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.
1	.00	5.2	18	.01	.00	.01	.00	.01	.01	.01	.00	.09
2	.00	.00	.01	.00	.00	3.9	.01	.01	.01	.01	.00	.00
3	.00	.01	.00	.00	.00	23	.00	.02	.01	.01	.00	.00
4	.00	.00	.00	.02	.00	.03	.00	.01	.01	.01	.00	.01
5	.00	.00	.00	1.6	.00	.01	.01	.01	.01	2.5	.00	.45
6	.01	.00	.00	.00	.00	.00	.01	.01	.02	.60	.00	.01
7	.03	.00	.00	.15	.58	.00	.01	.03	.01	.08	.00	.01
8	.03	.01	.00	.01	2.1	.00	.01	.02	.01	.01	.00	.01
9	.00	.01	.00	.02	.02	.00	.00	.01	64	.01	.00	.00
10	.00	.00	.00	.21	.01	.00	.01	.01	.02	.01	.00	.01
11	.00	.00	.00	.01	.01	.00	.01	.01	.01	.01	.01	.01
12	.00	.01	.00	.01	.00	.00	.01	.01	.00	.02	.00	.01
13	.00	.21	.00	.00	.00	.00	.01	.01	.00	.01	.00	.01
14	.00	.03	.00	.01	.00	.00	.00	.01	.00	.01	.00	.01
15	.00	.01	.00	.00	.00	.00	.00	.00	.00	.01	.00	.01
16	.00	.00	.00	.00	.00	.00	.00	.01	.00	.01	.00	.00
17	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.01
18	.00	.01	.00	.03	.00	.00	.00	.01	.00	.01	.00	.01
19	.00	.00	.00	.01	.00	.00	.00	.01	.00	.01	.00	.00
20	.00	.01	.00	.00	.00	.00	.00	.02	.00	.01	.00	.01
21	.00	.00	.00	.00	.00	.00	.00	.00	.00	.01	.00	.01
22	.00	.00	.00	.00	.01	.00	.00	.00	.00	.05	.00	.01
23	.00	.00	.00	.12	.01	.00	.00	.01	.14	.01	.00	.01
24	.00	.00	.00	10	.01	.00	.00	.01	.01	.01	.00	.12
25	.00	.00	.36	1,770	.01	.00	.00	.01	.01	.01	.00	.01
26	.00	.00	.01	.04	.02	.00	.00	.00	.01	.01	.00	.01
27	.00	.03	.00	4.6	1.1	.01	.00	.00	.01	5.2	.00	.01
28	.05	.00	.01	.45	1.7	.01	6.4	.01	.01	.00	.00	.01
29	.00	.00	.01	.00	.00	.01	.01	.02	.55	.00	.00	.01
30	.00	.07	1.5	.50	---	.02	.01	.01	.01	.00	.00	.01
31	.31	---	2.1	.01	---	.32	---	.01	---	.00	6.6	---
TOTAL	0.43	5.61	22.00	1787.81	5.58	27.32	6.51	0.31	64.87	8.65	6.61	0.88

Appendix 2.--Daily mean discharge (cubic feet per second) for water year 1997 at streamflow-gaging station 16273950, South Fork Kapunahala Stream at Kaneohe, Oahu, Hawaii
[e, estimated daily value; acre-ft, acre-feet]

Day	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.
1	e1.7	e1.6	e2.2	e2.2	e2.3	e2.1	e2.4	e2.3	e2.3	e2.2	e2.0	e1.9
2	e1.7	e2.2	e2.1	e2.4	e2.2	e2.1	e7.9	e2.3	e2.3	e2.2	e2.0	e1.9
3	e1.7	e1.8	e2.2	e11	e2.2	e2.0	e3.6	e2.3	e2.2	e2.2	e2.0	e1.9
4	e1.7	e1.7	e2.2	e6.1	e2.2	e2.4	e2.7	e2.3	e2.2	e2.2	e2.1	e1.9
5	e1.7	e5.9	e2.2	e2.5	e2.2	e5.8	e2.6	e2.6	e2.2	e2.1	e2.2	e1.8
6	e1.7	e2.2	e2.2	e2.3	e2.2	e2.2	e2.6	e2.6	e2.2	e2.3	e2.2	e1.9
7	e1.7	e1.9	e2.2	e2.2	e2.1	e2.1	e2.5	e3.1	e2.2	e2.2	e2.1	e1.9
8	e1.7	e6.5	e2.1	e2.1	e2.1	e2.0	e2.5	e7.1	e2.2	e2.2	e2.0	e1.8
9	e1.8	e2.1	e1.9	e2.1	e2.1	e2.1	e2.4	e2.6	e2.1	e2.3	e2.0	e1.8
10	e1.8	e1.9	e1.9	e2.1	e2.1	e2.1	e2.5	e2.5	e2.0	e2.3	e2.0	e1.8
11	e1.8	e1.8	e1.9	e2.0	e2.0	e5.6	e2.6	e2.6	e2.0	e2.2	e2.1	e1.9
12	e1.8	e8.6	e2.0	e2.0	e2.0	e2.1	e2.4	e2.8	e2.0	e2.2	e2.1	e2.4
13	e1.8	e8.0	e2.0	e2.0	e2.0	e2.2	e2.4	e2.5	e2.0	e2.3	e2.0	e2.1
14	e1.8	e9.6	e2.0	e2.0	e2.0	e2.0	e2.3	e6.8	e2.1	e2.3	e2.0	e2.1
15	e1.8	e3.4	e2.0	e2.0	e2.0	e2.4	e2.3	e6.2	e2.1	e2.3	e2.0	e2.0
16	e1.8	e7.4	e2.0	e2.1	e2.0	e2.1	e2.3	e3.1	e2.1	e2.2	e2.2	e2.0
17	e1.8	e6.5	e2.0	e2.0	e2.2	e9.4	e2.3	e2.7	e2.1	e2.2	e5.5	e1.9
18	e1.7	e2.8	e2.0	e2.0	e2.0	e2.5	e2.3	e2.6	e2.1	e2.1	e2.2	e1.8
19	e2.1	e2.6	e1.9	e7.0	e2.0	e2.2	e2.3	e2.5	e2.2	e2.4	e2.0	e1.9
20	e1.8	e2.5	e1.9	e3.1	e2.2	e2.2	e2.3	e2.4	e2.2	e2.0	e1.9	2.1
21	e1.7	e2.4	e2.0	e3.4	e2.2	e2.3	e2.3	e2.4	e2.3	e2.1	e1.9	2.7
22	e1.6	e2.2	e2.0	e2.6	e5.3	e2.3	e2.3	e2.5	e2.2	e3.8	e1.9	2.0
23	e1.6	e2.3	e2.1	e2.3	e2.2	e8.5	e2.2	e2.6	e2.2	e2.4	e1.9	1.9
24	e1.6	e2.8	e2.1	e2.2	e2.0	e2.9	e2.4	e2.5	e2.3	e2.2	e1.9	1.8
25	e1.5	e2.3	e2.0	e2.3	e2.0	e2.8	e2.4	e2.4	e2.2	e2.2	e1.9	1.8
26	e1.6	e2.3	e2.2	e2.2	e2.3	e2.6	e5.3	e2.4	e2.4	e2.1	e2.0	1.8
27	e1.6	e2.2	e2.8	e2.2	e2.3	e2.5	e2.7	e2.4	e2.4	e2.0	e1.9	1.8
28	e1.6	e2.2	e2.1	e2.2	e2.0	e2.6	e2.4	e2.3	e2.2	e2.0	e1.9	1.8
29	e1.6	e2.2	e2.0	e2.5	---	e2.4	e2.3	e2.3	e2.3	e2.0	e2.0	1.8
30	e1.6	e2.2	e2.0	e2.4	---	e2.3	e2.3	e2.3	e2.3	e2.0	e1.9	1.8
31	e1.6	---	e2.3	e2.4	---	e2.2	---	e2.2	---	e2.0	e2.0	---
Total	53.0	104.1	64.5	87.9	62.4	91.0	81.8	90.2	65.6	69.2	65.8	58.0
Mean	1.71	3.47	2.08	2.84	2.23	2.94	2.73	2.91	2.19	2.23	2.12	1.93
Max.	2.1	9.6	2.8	11	5.3	9.4	7.9	7.1	2.4	3.8	5.5	2.7
Min.	1.5	1.6	1.9	2.0	2.0	2.0	2.2	2.2	2.0	2.0	1.9	1.8
Acre-ft	105	206	128	174	124	180	162	179	130	137	131	115

Appendix 3. --Daily mean sediment discharge (tons/day) for water year 1997 at sediment-gaging station 16273950, South Fork Kapunahala Stream at Kaneohe, Oahu, Hawaii
[e, estimated daily value]

Day	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.
1	e.09	e.08	e.06	e.07	e.14	e.12	e.06	e.14	e.09	e.14	e.12	e.12
2	e.10	e.22	e.05	e.08	e.13	e.12	e4.0	e.13	e.12	e.13	e.12	e.12
3	e.11	e.13	e.05	e7.8	e.12	e.11	e.32	e.13	e.09	e.12	e.12	e.12
4	e.12	e.09	e.05	e2.4	e.12	e.27	e.11	e.13	e.09	e.11	e.12	e.12
5	e.13	e3.2	e.05	e.13	e.12	e2.2	e.11	e.34	e.10	e.10	e.13	e.12
6	e.14	e.12	e.05	e.11	e.12	e.14	e.11	e.23	e.10	e.13	e.13	e.12
7	e.15	e.11	e.05	e.09	e.12	e.12	e.07	e.28	e.10	e.10	e.11	e.12
8	e.16	e3.9	e.05	e.09	e.11	e.12	e.07	e3.5	e.10	e.09	e.09	e.12
9	e.19	e.06	e.05	e.10	e.11	e.12	e.06	e.25	e.10	e.12	e.09	e.12
10	e.18	e.05	e.05	e.10	e.11	e.12	e.07	e.15	e.09	e.12	e.08	e.12
11	e.17	e.04	e.10	e.10	e.11	e2.3	e.11	e.23	e.09	e.11	e.07	e.12
12	e.16	e6.9	e.06	e.11	e.11	e.13	e.07	e.29	e.08	e.11	e.06	e.18
13	e.15	e6.0	e.06	e.12	e.11	e.13	e.07	e.16	e.06	e.12	e.07	e.14
14	e.14	e8.8	e.27	e.12	e.11	e.12	e.07	e3.4	e.05	e.12	e.09	e.15
15	e.13	e.14	e.06	e.12	e.11	e.16	e.07	e2.8	e.05	e.12	e.11	e.14
16	e.13	e5.1	e.06	e.12	e.11	e.14	e.07	e.32	e.03	e.11	e.16	e.16
17	e.12	e2.5	e.05	e.11	e.12	e9.7	e.07	e.24	e.03	e.11	e2.0	e.17
18	e.11	e.11	e.05	e.11	e.11	e.24	e.07	e.20	e.04	e.11	e.14	e.14
19	e.34	e.09	e.05	e3.5	e.11	e.14	e.07	e.12	e.06	e.16	e.12	e.10
20	e.12	e.06	e.05	e.79	e.12	e.14	e.07	e.12	e.08	e.10	e.11	.13
21	e.12	e.06	e.05	e.63	e.12	e.14	e.07	e.11	e.11	e.12	e.11	.53
22	e.12	e.05	e.05	e.27	e2.1	e.14	e.07	e.11	e.08	e.57	e.11	.15
23	e.14	e.05	e.05	e.15	e.12	e5.7	e.07	e.18	e.10	e.14	e.11	.11
24	e.14	e.17	e.05	e.14	e.11	e.22	e.08	e.11	e.11	e.14	e.11	.09
25	e.11	e.06	e.05	e.15	e.11	e.15	e.08	e.11	e.12	e.14	e.11	.09
26	e.09	e.06	e.10	e.14	e.22	e.08	e1.9	e.10	e.14	e.13	e.13	.08
27	e.07	e.06	e.20	e.14	e.15	e.05	e.36	e.10	e.15	e.12	e.12	.08
28	e.06	e.06	e.06	e.13	e.11	e.08	e.14	e.10	e.11	e.12	e.11	.07
29	e.04	e.06	e.05	e.16	---	e.05	e.14	e.10	e.13	e.12	e.13	.07
30	e.06	e.06	e.05	e.14	---	e.06	e.14	e.10	e.14	e.12	e.12	.07
31	e.08	---	e.09	e.14	---	e.05	---	e.09	---	e.12	e.12	---
Total	3.97	38.39	2.12	18.36	5.36	23.36	8.77	14.37	2.74	4.17	5.32	3.97