Prepared in cooperation with the City and County of Honolulu Department of Environmental Services

Sources of Suspended Sediment in the Waikele Watershed, O‘ahu, Hawai‘i

Scientific Investigations Report 2012–5085

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

Cover:
Aerial view of middle and lower Waikele watershed, O‘ahu, Hawai‘i—agriculture fields in foreground; Waikele Stream gulch in middle; Pearl Harbor, Ko‘olau Mountains, and Diamond Head in the background. (Photographed August 1, 2012)

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By Scot K. Izuka

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KEN SALAZAR, Secretary

U.S. Geological Survey
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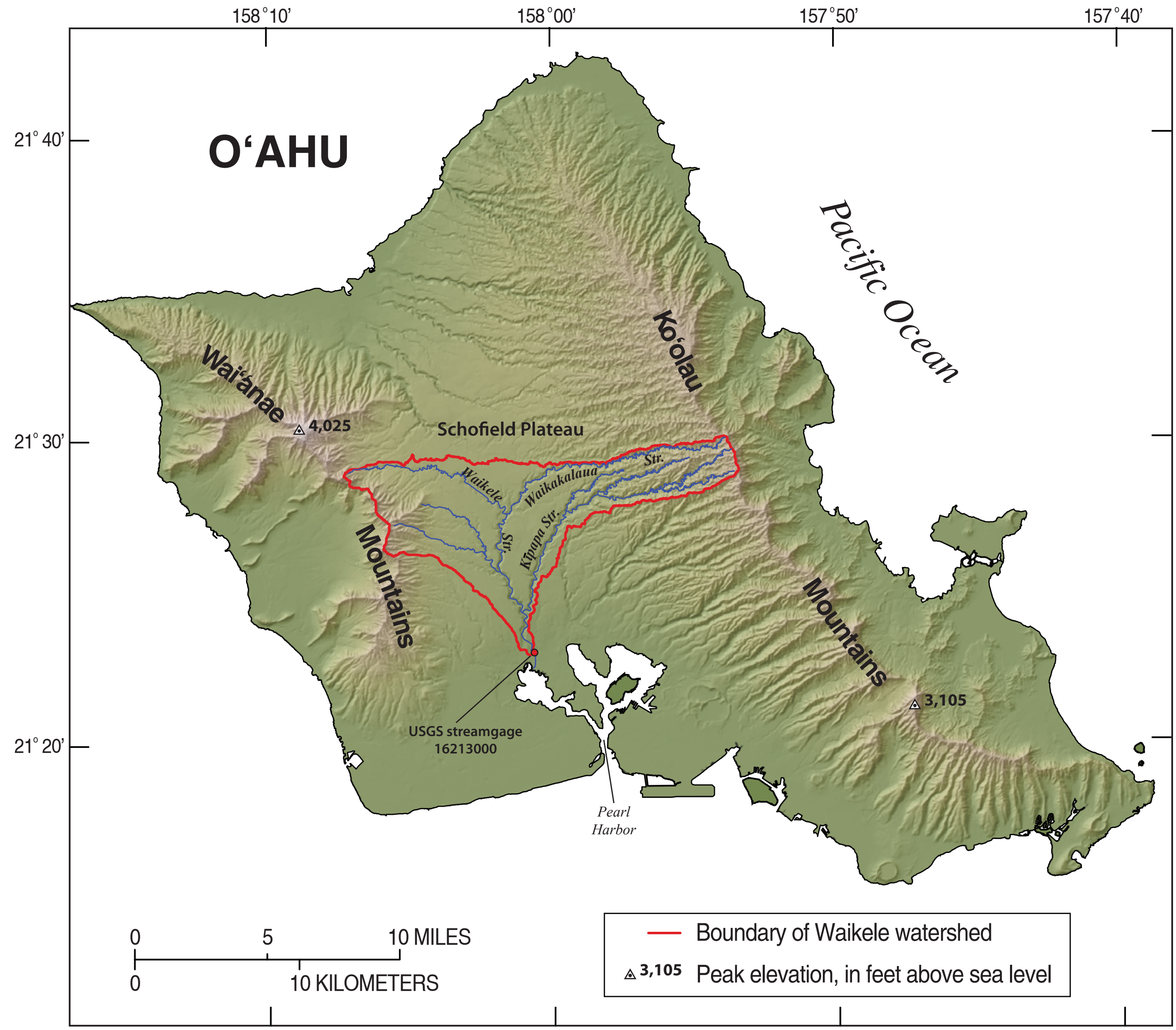
Executive Summary

Introduction

Waikele Stream and its tributaries, Waikakalaua Stream and Kīpapa Stream, drain a 45-square-mile area that lies between the Wai‘anae Mountains and the Ko‘olau Mountains, the two principal mountain ranges on O‘ahu, a basaltic shield-volcano island in Hawai‘i (fig. ES1). The streams converge on the saddle between the mountains known as the Schofield Plateau, then flow southward and discharge into Pearl Harbor. Runoff from the Waikele watershed carries sediment to Waikele Stream and Pearl Harbor. The U.S. Environmental Protection Agency recognizes excessive sediment as a leading cause of water-quality impairment in the United States. Understanding the sources of sediment in a watershed is essential to developing strategies to manage sediment in water bodies. The purpose of this study is to identify sources of suspended sediment in the Waikele watershed. The study was conducted by the U.S. Geological Survey (USGS) in cooperation with the City and County of Honolulu, Department of Environmental Services.

Setting—Rainfall in the Waikele watershed ranges from about 25 inches per year at the mouth of the stream where



Topographic base from U.S. Geological Survey (2003) 10-meter digital elevation model, Universal Transverse Mercator projection, Zone 4, North American Datum of 1983

Figure ES1. Waikele watershed, O‘ahu, Hawai‘i.

it empties into Pearl Harbor to more than 240 inches per year in the Koʻolau Mountains. In the upper part of the watershed, the Koʻolau Mountains have narrow valleys with only a ribbon of alluvium, whereas the Waiʻanae Mountains have broader, more extensively alluviated valleys. In the middle reaches of the watershed, streams have cut deep gulches into the Schofield Plateau; between the gulches are extensive interfluves of relatively low relief and thick residual saprolite. Alluvium exists at the bottom of the gulches, but in some places alluvium is thin or absent. Alluvium throughout most of the Waikele watershed is coarse, consisting mostly of boulders and cobbles, but some larger clasts are formed of highly weathered basalt that can disintegrate quickly during stream transport and contribute to the suspended-sediment load.

The Waikele watershed was the site of large-scale pineapple and sugarcane cultivation throughout most of the 20th century, but both industries began to decline between the 1960s and 1990s. Sugarcane agriculture on Oʻahu ceased in the 1990s; pineapple cultivation continues but the industry is in flux. Much of the land formerly used for sugarcane and pineapple cultivation currently lies fallow or is covered by grass and shrub. Some land has been converted to diversified agriculture, agricultural research, or urban land use (fig. ES2). Two large military bases (Schofield Barracks and Wheeler Army Airfield) and several golf courses are also located in the watershed. The upper elevations of the watershed, particularly in the Koʻolau Mountains, are forested conservation areas that are largely undeveloped.

Study Approach

Data for this study were collected in the period October 1, 2007, through September 30, 2010. Sediment yields from the watershed and four subbasins in the watershed were studied using data from four automated streamflow/sediment gages (Kīpapa, Wheeler, Waipahu, and Mililani; fig. ES2). Changes in channel-bed sediment storage were determined from annual surveys of channel cross sections. Estimates of suspended-sediment yields from hillslopes, channel beds, and various land uses were computed for the Waikele watershed from the gage and channel-storage data.

Results

Daily mean streamflow and suspended-sediment data from this study are stored in the USGS National Water Information System (NWIS) database and are available through the NWIS website (*http://waterdata.usgs.gov/nwis*). Computed suspended-sediment yields from this study are presented in table ES1. Results for the Waipahu gage represent the Waikele watershed as a whole. Results for the Wheeler, Kīpapa, and Mililani gages represent subbasins within the watershed. Results for the Waipahu Exclusive subbasin represent the remainder of the watershed not covered by the other subbasins (fig. ES2).

Storm of December 11, 2008, had Substantial Impact on Study-Period Results—Streamflow on average during the study period was lower than in previous decades (table ES2), but a storm on December 11, 2008, generated a peak stream flow of 22,600 cubic feet per second—the highest flow in the 59-year period of record at the Waipahu gage—and had a substantial impact on suspended-sediment transport. Suspended-sediment load on the day of the storm accounted for more than 90 percent of the study-period suspended-sediment yield from the Waikele watershed. The average yield during the study period was 3.5 times higher than the average yield during the 21 years prior to this study and 2.7 times higher than the average for the entire 24 years of available record for the Waipahu gage. The streamflows and suspended-sediment loads of the study period are, however, consistent with data from throughout the gage's period of record in showing that a vast majority of suspended-sediment transport occurs during a few large storms; these results are also consistent with previous erosion and sediment-transport studies on Oʻahu.

Hillslopes are the Main Source of Suspended Sediment—During this study, most of the suspended-sediment yield from the Waikele watershed came from hillslopes (areas between stream channels). Only a few percent came from channel storage (table ES1). Hillslopes in the watershed yielded 81,900 tons per year during the period compared to only 626 tons per year from channel storage.

Agricultural Land Use Accounts for Most of the Suspended Sediment Yield—The Kīpapa subbasin, which encompasses an area that is entirely covered by forest land use, had a hillslope suspended-sediment yield of 386 tons per year per square mile (tons/yr/mi^2) during the study period (table ES1); this value is within the range of values reported for other forested valleys in wet climates in Hawaiʻi. The Mililani subbasin, which encompasses an area that is covered entirely by urban land use, had a relatively low yield per square mile (25 tons/yr/mi^2), probably because pavement, buildings, storm drains, and maintained grassy areas in the mature residential development of Mililani reduce erosion. Extrapolating the results from the Mililani and Kīpapa subbasins to urban and forest areas in the Waipahu Exclusive subbasin, and using a range to account for uncertainty, suspended-sediment yield from agricultural land use was estimated to be between 5,580 and 6,440 tons/yr/mi^2 during the study period (table ES3). Inasmuch as this estimate is based on a study period in which average suspended-sediment yield from the watershed was about 2.7 times greater than the long-term mean, the long-term suspended-sediment yield from agricultural land may be closer to 2,070 to 2,390 tons/yr/mi^2, which is generally comparable to previous studies of agricultural sediment yield from areas in the Waikele watershed as well as areas outside Hawaiʻi. Of the three land uses considered, agriculture had by far the highest suspended-sediment yield per square mile during this study—about an order of magnitude higher than forests and two orders of magnitude higher than urban areas.

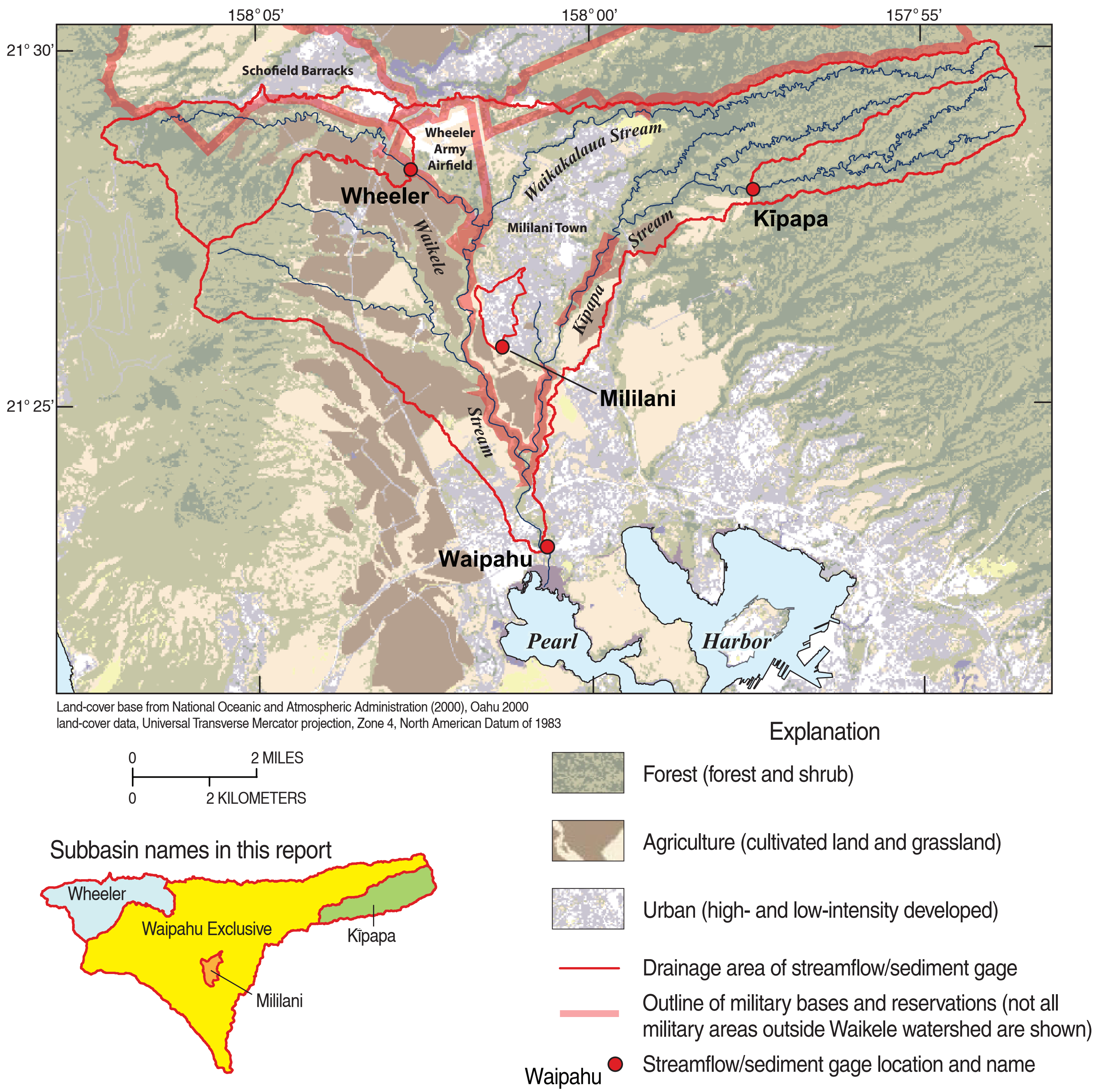


Figure ES2. Streamflow/sediment gages, subbasin outlines, and land use in the Waikele watershed, O'ahu, Hawai'i. Land use (forest, agriculture, and urban) interpreted from land-cover categories (shown in parentheses) in National Oceanic and Atmospheric Administration (2000). Outline of military bases and reservations are from the U.S. Geological Survey (2003); only military areas that are within or partly within the Waikele watershed are shown.

Table ES1. Suspended-sediment yield for the Waikele watershed and its subbasins, O‘ahu, Hawai‘i, during period of this study (water years 2008 to 2010).

[Negative change in channel storage indicates erosion. WY, water year, which year begins October 1 of the previous calendar year and ends September 30; tons/yr, tons per year; tons/yr/mi^2, tons per year per square mile]

Water year	Yield (tons/yr)	Change in channel storage (tons/yr)	Yield from hillslopes (tons/yr)	Percentage of basin yield from		Normalized hillslope yield (tons/yr/mi^2)
				Channels	Hillslopes	
Wheeler subbasin						
2008	650	-80	570	12	88	85
2009	7,070	357	7,430	0	100	1,110
2010	88	-34	54	39	61	8.0
Study period	2,600	81	2,680	0	100	399
Kīpapa subbasin						
2008	1,460	-11	1,450	1	99	339
2009	2,910	54	2,970	0	100	694
2010	680	-139	540	20	80	126
Study period	1,690	-32	1,650	2	98	386
Mililani subbasin						
2008	16	assumed negligible	16	assumed negligible	100	29
2009	16	assumed negligible	16	assumed negligible	100	29
2010	9.4	assumed negligible	9.4	assumed negligible	100	17
Study period	14	assumed negligible	14	assumed negligible	100	25
Waipahu Exclusive subbasin						
2008	11,800	80	11,900	0	100	354
2009	220,000	-1,510	218,000	1	99	6,520
2010	2,710	-594	2,120	22	78	63
Study period	78,200	-675	77,500	1	99	2,310
Entire Waikele watershed (represented by Waipahu drainage basin)						
2008	14,000	-10	13,900	0	100	308
2009	230,000	-1,100	229,000	0	100	5,070
2010	3,490	-768	2,720	22	78	60
Study period	82,500	-626	81,900	1	99	1,810

Table ES2. Summary of streamflow and suspended-sediment data collected prior to the period of this study from gages in the Waikele watershed, O‘ahu, Hawai‘i.

[WY, water year, which year begins October 1 of the previous calendar year and ends September 30; ft^3/s, cubic feet per second; $ft^3/s/mi^2$, cubic feet per second per square mile; tons/yr, tons per year; $tons/yr/mi^2$, tons per year per square mile]

Kīpapa gage streamflow		
Statistic	**WY1957–WY2004**	**This study**
Highest daily mean	852 ft^3/s	372 ft^3/s
Lowest daily mean	0.00 ft^3/s	0.00 ft^3/s
Average	10 ft^3/s	7.6 ft^3/s
Average runoff	2.5 $ft^3/s/mi^2$	1.8 $ft^3/s/mi^2$
Kīpapa gage sediment		
Statistic	**WY1973–WY1982**	**This study**
Highest daily load	7,870 tons	2,350 tons
Lowest daily load	0.00 tons	0.00 tons
Average annual load	5,060 tons/yr	1,690 tons/yr
Normalized average basin yield	1,180 $tons/yr/mi^2$	395 $tons/yr/mi^2$
Waipahu gage streamflow		
Statistic	**WY1951–WY2007**	**This study**
Highest daily mean	2,590 ft^3/s	4,270 ft^3/s
Lowest daily mean	0.61 ft^3/s	9.4 ft^3/s
Average	40 ft^3/s	33 ft^3/s
Average runoff	0.88 $ft^3/s/mi^2$	0.73 $ft^3/s/mi^2$
Waipahu gage sediment		
Statistic	**WY1972–WY1993**	**This study**
Highest daily load	32,900 tons	227,000 tons
Lowest daily load	0.01 tons	0.09 tons
Average load	23,600 tons/yr	82,500 tons/yr
Normalized average basin yield	522 $tons/yr/mi^2$	1,830 $tons/yr/mi^2$

Table ES3. Estimated suspended-sediment yields from land uses in the Waipahu Exclusive subbasin, Waikele watershed, O‘ahu, Hawai‘i, during the period of this study (water years 2008 to 2010).

[$tons/yr/mi^2$, tons per year per square mile; mi^2, square mile; tons/yr, tons per year]

Land use	Estimated normalized yield for study period ($tons/yr/mi^2$)	Waipahu Exclusive subbasin		
		Area (mi^2)	Yield (tons/yr)	Percent of total yield
Urban	12–50	5.19	62–260	0.1–0.4
Forest	193–772	16.87	3,260–13,000	4.2–16.8
Agriculture	5,580–6,440	11.51	64,200–74,200	82.9–95.7

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Conversion Factors

Multiply	By	To obtain
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
square foot (ft^2)	0.09290	square meter (m^2)
gallon (gal)	3.785	liter (L)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
inch per hour (in/h)	0.0254	meter per hour (m/h)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
ton[1]	0.9072	megagram (Mg)
ton per day per square mile (tons/yr/mi^{2})	0.3503	megagram per day per square kilometer (Mg/yr/km^2)
ton per year (ton/yr)	0.9072	metric ton per year
pound per cubic foot (lb/ft^3)	0.01602	gram per cubic centimeter (g/cm^3)

[1] short ton, equivalent to 2,000 pounds

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:
°F=(1.8×°C)+32
Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:
°C=(°F-32)/1.8
Vertical coordinate information is referenced to mean sea level.
Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).
Elevation refers to distance above the vertical datum.
Suspended-sediment concentrations in water are given in milligrams per liter (mg/L).

Sources of Suspended Sediment in the Waikele Watershed, Oʻahu, Hawaiʻi

By Scot K. Izuka

Abstract

Data from streamflow/sediment gages and measurements of changes in channel-bed sediment storage were gathered between October 1, 2007, and September 30, 2010, to assess the sources of suspended sediment in the Waikele watershed, Oʻahu, Hawaiʻi. Streamflow from the watershed averaged 33 cubic feet per second during the study period, with interannual variations corresponding with variations in the frequency and magnitude of storm-flow peaks. Average streamflow during the study period was lower than the long-term average, but the study period included a storm on December 11, 2008, that caused record-high streamflows in parts of the watershed.

Suspended-sediment yield from the Waikele watershed during the study period averaged 82,500 tons per year, which is 2.7 times higher than the long-term average. More than 90 percent of the yield during the study period was discharged during the December 11, 2008, storm. The study-period results are consistent with long-term records that show that the vast majority of suspended-sediment transport occurs during a few large storms. Results of this study also show that all but a small percentage of the suspended-sediment yield came from hillslopes. Only a small fraction of bed sediments is fine enough to be transported as suspended load; most bed sediments in the watershed are coarse. Silt and clay constitute less than 3 percent of the bed-sediment volume on average. Some larger clasts, however, can disintegrate during transport and contribute to the suspended load downstream.

During the study period, suspended-sediment yield from the urbanized Mililani subbasin averaged 25 tons per year per square mile (tons/yr/mi^2), which was much smaller than the yield from any other subbasin; these results indicate that urban land use yields much less sediment than other land uses. The wet, forested Kīpapa subbasin had an average normalized hillslope suspended-sediment yield of 386 tons/yr/mi^2; the average yield for forested areas in the watershed may be lower. Suspended-sediment yield from agricultural land use in the watershed is estimated to range between 5,590 and 6,440 tons/yr/mi^2 during the study period; the long-term average is estimated to be 2,070 to 2,390 tons/yr/mi^2. Of the three land uses considered, agriculture had by far the highest normalized suspended-sediment yield during this study—about an order of magnitude higher than forests and two orders of magnitude higher than urban areas.

Introduction

Waikele Stream and its tributaries, Waikakalaua Stream and Kīpapa Stream, drain a 45 mi^2 area that lies between the Waiʻanae Mountains (peak elevation 4,025 ft) and the Koʻolau Mountains (peak elevation 3,105 ft), the two principal mountain ranges on Oʻahu, Hawaiʻi (fig. 1). The streams converge on the saddle between the mountains known as the Schofield Plateau, then flow southward and discharge into Pearl Harbor. Runoff from the Waikele watershed carries sediment to Waikele Stream and Pearl Harbor. Excessive sediments in rivers, streams, and lakes in the United States have been recognized as a leading cause of water quality impairment (U.S. Environmental Protection Agency, 1996). Excess deposition of sediment can affect aquatic life and habitats as well as human activities such as recreation, navigation, and water supply, and sediment can carry other contaminants such as nutrients and toxic chemicals to water bodies (U.S. Environmental Protection Agency, 1996, 2011).

Sediment yield from a watershed is a function of several natural and anthropogenic factors, such as geology, climate, slope, and land use. The watershed of Waikele Stream encompasses a variety of land uses, including agriculture and urban development, as well as undeveloped conservation land in the mountains (Klasner and Mikami, 2003). Urbanization can cause the sediment yield of a basin to change from what it was under natural vegetation (Dunne and Leopold, 1978). The substantial effect of agriculture on increasing soil erosion is well known (for example, Dunne and Leopold, 1978; Montgomery, 2007), although the effect differs by crop type, cultivation method, and land management. Understanding the sources of sediment in a watershed is essential to developing strategies to manage sediment in water bodies.

Purpose and Scope.—The purpose of this study is to identify sources of suspended sediment in the Waikele watershed during a 3-year monitoring period beginning October 1, 2007. In this study, the Waikele watershed is defined by the drainage area of the U.S. Geological Survey streamgage 16213000 on Waikele Stream at Waipahu (fig. 1).

Acknowledgments

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Setting

Oʻahu is a 604-mi^2 island in the tropical trade-wind belt of the North Pacific Hawaiian Archipelago. The island was built by two Tertiary-age basaltic shield volcanoes, the eroded, faulted remnants of which are the Koʻolau and Waiʻanae Mountains (fig. 1). The Schofield Plateau is a high saddle that formed between the two mountains as lava flows from the younger Koʻolau shield volcano buried the eroded northeastern flank of the older Waiʻanae shield volcano (Stearns and Vaksvik, 1935; Langenheim and Clague, 1987; Sherrod and others, 2007).

The climate of Oʻahu is characterized by mild temperatures, moderate humidity, and northeasterly trade winds. Rainfall distribution is influenced by the orographic effect and the prevailing northeasterly trade winds. Mean annual rainfall is more than 260 in. over the crest of the Koʻolau Mountains, 35 to 65 in. over the

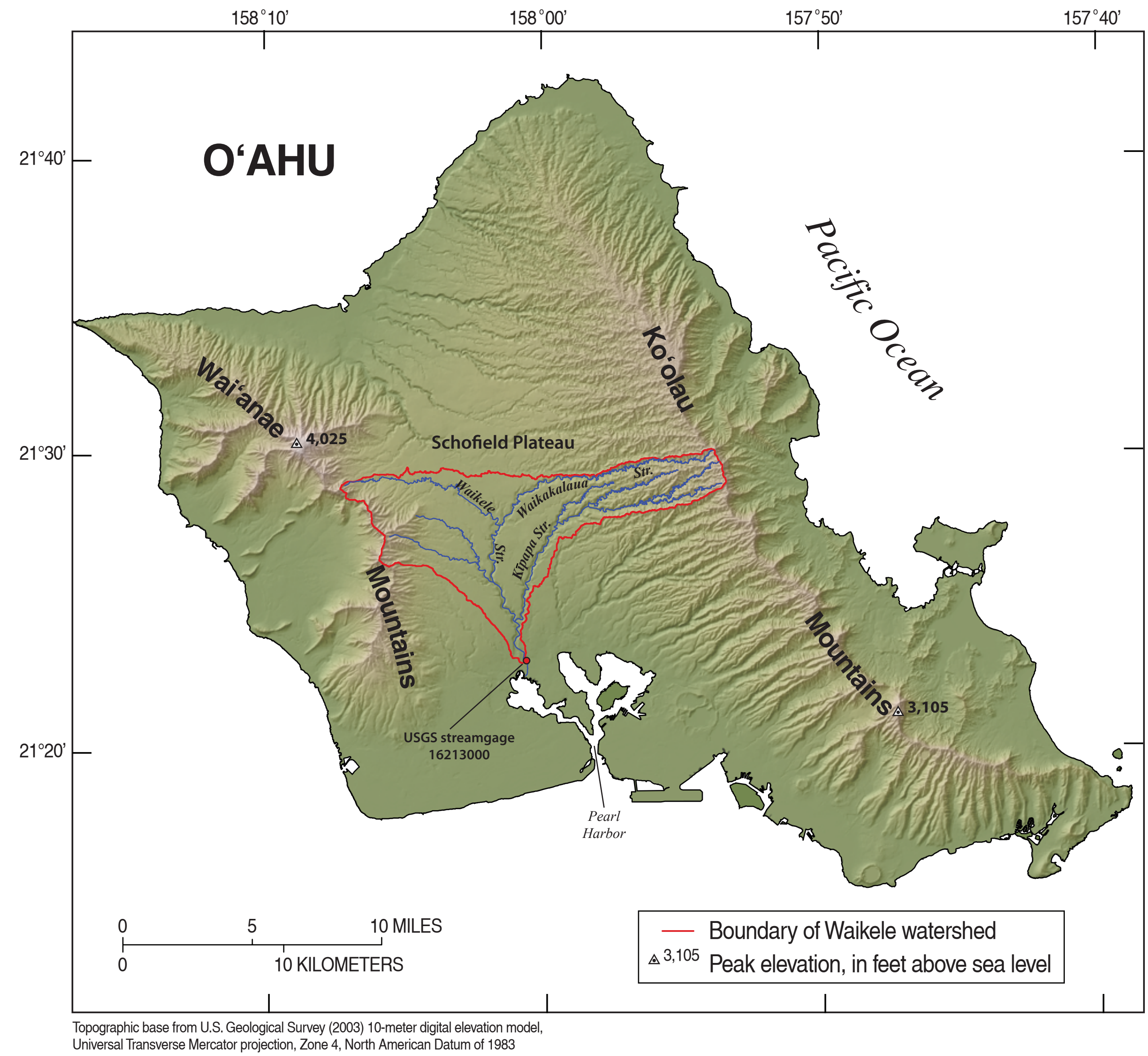
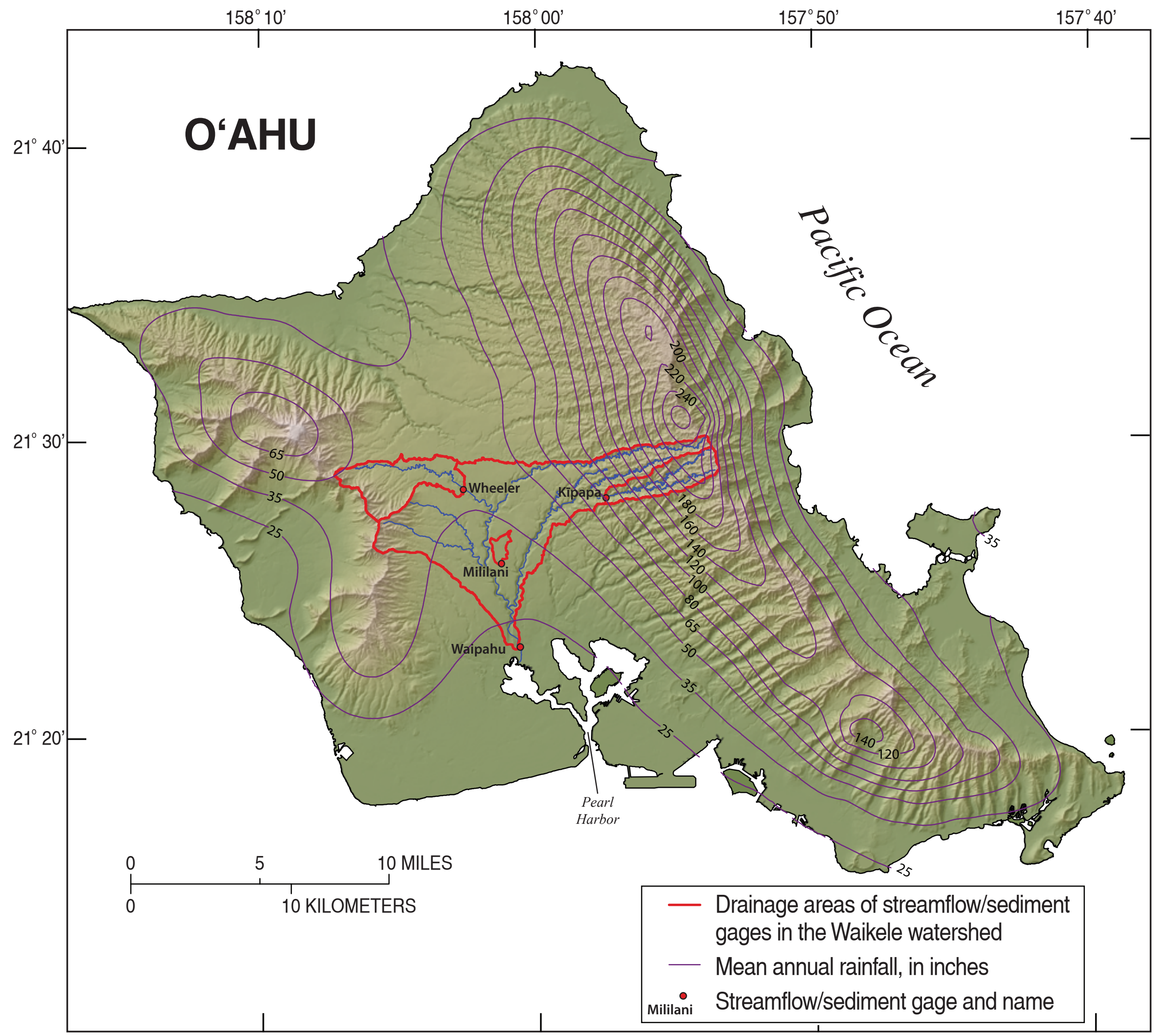


Figure 1. Map showing Waikele watershed, Oʻahu, Hawaiʻi.

Schofield Plateau, and about 65 in. over the crest of the Wai‘anae Mountains (Giambelluca and others, 2011) (fig. 2). Within the Waikele watershed, rainfall ranges from about 25 in/yr at the mouth of the stream where it empties into Pearl Harbor to more than 240 in/yr in the Ko‘olau Mountains. Winter months are generally wetter than summer months, with monthly mean rainfall highest in January and lowest in June to July (Giambelluca and others, 1986).

The upper reaches of the watershed extend into amphitheater-headed valleys that are typical of the stream-dissected flanks of the Ko‘olau and Wai‘anae Mountains (Jones, 1938; Stearns and Vaksvik, 1935; Macdonald and others, 1983). Erosion in these valleys is a combination of stream downcutting and episodic mass-wasting events (Scott and Street, 1978; Macdonald and others, 1983). The central-leeward side of the Ko‘olau Mountains, including areas in the Waikele watershed, are dissected by narrow, v-shaped valleys (fig. 3*A*) that have only a very narrow ribbon of alluvium; this is in contrast to the relatively wide, alluviated, flat-floored valleys on the windward and southeast-leeward flanks of the Ko‘olau Mountains (Stearns and Vaksvik, 1935). The bedrock can be deeply weathered, however, particularly in the wet, upper parts of the valleys (Wentworth, 1951; Izuka, 1992). In the Wai‘anae Mountains, valleys are wider and more extensively alluviated than in the leeward-central Ko‘olau Mountains (Stearns and Vaksvik, 1935). This indicates that the valleys on the Wai‘anae side of the watershed are in a more advanced stage of erosion and alluviation than the valleys on the Ko‘olau side, which is not consistent with the present distribution of rainfall (fig. 2). Erosion and alluviation of the Wai‘anae Mountains probably achieved its more advanced state before the younger Ko‘olau Mountains formed a barrier to orographic rainfall generated by the northeast trade winds (Stearns and Vaksvik, 1935; Macdonald and others, 1983).



Topographic base from U.S. Geological Survey (2003) 10-meter digital elevation model, Universal Transverse Mercator projection, Zone 4, North American Datum of 1983

Figure 2. Map showing distribution of mean annual rainfall on O‘ahu, Hawai‘i (modified from Giambelluca and others, 2011).

In the middle reaches of the watershed, Waikele Stream and its tributaries have cut gulches as much as a few hundred feet deep into the Schofield Plateau. Between the gulches are extensive interfluves of relatively low relief (fig. 3*B*). Chemical weathering has transformed the basalt lava flows at the surface into soft residual saprolite that may be as much as 100 ft thick (Stearns and Vaksvik, 1935). Alluvium exists at the bottom of the gulches, but in some places alluvium is thin or is absent and weathered bedrock is exposed in the bottom of stream channels (fig. 4*A*).

Alluvium throughout most of the Waikele watershed consists mostly of boulders and cobbles, but finer sediment may predominate in some reaches (fig. 4*B*). Unlike the granitic rocks that commonly form continental mountains, the basaltic rocks that form mountains in Hawaiʻi are composed largely of finely crystalline mafic minerals that weather quickly to clays and oxides (Wentworth, 1928; Macdonald and others, 1983). Larger alluvial clasts such as pebbles, cobbles, and boulders form from residual kernels of unweathered basalt and are loosened from the otherwise weathered bedrock during erosion. Some clasts, particularly small pebbles and sand, are composed of highly weathered basalt that can disintegrate during stream transport and contribute to the suspended-sediment load (Hill and others, 1998).

Streams on Oʻahu are typically flashy because of their small drainage basins and steep gradients (Wong, 1994). The hydrographs for storm-generated streamflows for most streams on Oʻahu rise, peak, and recede in a few hours (Wu, 1969). Many streams on Oʻahu have both perennial and intermittent reaches. In perennial reaches, the storm-flow peaks are superimposed on persistent base flow generated by groundwater discharge. In intermittent reaches, water seeps from the stream into the ground. Most reaches of Waikele Stream and its tributaries are intermittent because the groundwater table is a few tens to

Figure 3. Aerial views of Waikele watershed, Oʻahu, Hawaiʻi, photographed on August 1, 2011. (*A*) V-shaped valley in upper watershed, Koʻolau Mountains. Kīpapa Stream and its streamflow/sediment gage are visible at bottom left. (*B*) Middle reaches of watershed where gulches dissect the gently sloping Schofield Plateau. View looks north from a point approximately above cross-section group WK3; Waikele Stream is in the gulch partially shown on the right edge of the photograph.

hundreds of feet below the land surface (Stearns and Vaksvik, 1935; Hunt, 1996; Oki, 1998). A notable exception is near the coast, where groundwater discharges from springs at the contact between the basalt aquifer and the inland limit of overlying semi-confining coastal sediments (Stearns and Vaksvik, 1935). Springs surrounding Pearl Harbor, including springs that discharge into lower Waikele Stream, are collectively known as the Pearl Harbor Springs (Stearns and Vaksvik, 1935; Wentworth, 1951). Hydrographs from lower Waikele Stream thus show substantial base flow that persists during dry periods.

Central O‘ahu was the site of large-scale pineapple and sugarcane cultivation throughout most of the 20th century. Sugarcane was grown primarily in the lower elevations where it could be irrigated by water from ditch systems, and pineapple was grown in the upper elevations (Wentworth, 1951). Both the pineapple and sugarcane industries in the watershed declined between the 1960s and 1990s. Sugarcane agriculture on O‘ahu ceased in the 1990s. Pineapple cultivation continues on O‘ahu today, but the industry is in flux. The pineapple industry closed its O‘ahu canning operations in the 1990s and reduced its production to fresh fruit only. Del Monte Fresh Produce, the major pineapple grower in the watershed, stopped planting in 2006 (Honolulu Star-Bulletin, 2006). Much of the land formerly used by the sugarcane and pineapple industries currently lies fallow or is covered by grass and shrub, but some land has been converted to diversified agriculture, agricultural research, or urban use (fig. 3*B*). Two large military bases (Schofield Barracks and Wheeler Army Airfield) and several golf courses are also located in Central O‘ahu. The upper elevations of Central O‘ahu, particularly in the Ko‘olau Mountains, are forested conservation areas that are largely undeveloped (figs. 3*A* and 5).

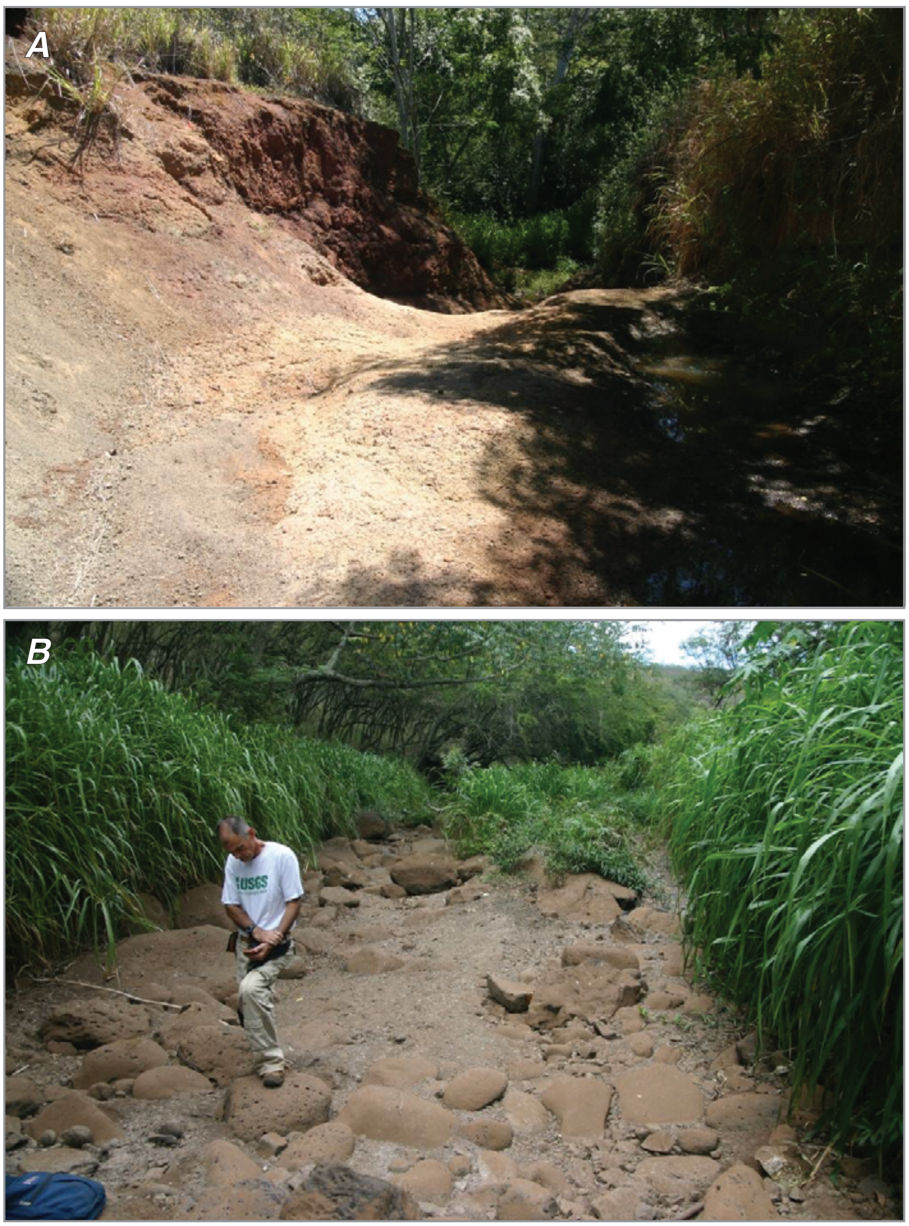


Figure 4. Photographs of Waikele Stream, O‘ahu, Hawai‘i. (*A*) Deeply weathered bedrock channel with no alluvium, and (*B*) alluvium in channel, near cross-section group WK3. Photographs taken in 2007.

Methods

In this report, “load” refers to the amount of sediment transported by a stream past a point, such as the site of a streamflow/sediment gage. “Yield” refers to the amount of sediment that comes from a specified source, such as a drainage basin, channels or hillslopes, or a particular land use. Both “load” and “yield” can be expressed as mass alone or as mass divided by time. When comparing yields from drainage basins of different sizes, it is helpful to express it as mass per area, which is referred to as “normalized yield” in this report.

Sources of suspended sediment in the watershed include hillslopes and stream channels. For the purposes of discussion in this report, hillslopes are defined as all areas outside stream channels shown on the U.S. Geological Survey 1:24,000-scale topographic maps (U.S. Geological Survey, 2006) and include undissected slopes as well as rills and gullies. Sediment eroded from hillslopes can be transported to stream channels by flowing water. Some of this sediment is transported out of the watershed by the stream, whereas some sediment can be stored temporarily in the stream channel under certain conditions, and removed from the channel under other conditions (Leopold and others, 1964).

The amount of suspended sediment yielded by the watershed is the sum of the sediment yield from hillslopes and channels:

$$Y_T = Y_H + Y_C, \qquad \text{(eq. 1)}$$

where Y_T is the total watershed yield, Y_H is the yield from hillslopes, and Y_C is the yield from channels (these quantities can be expressed in units of mass [M], mass per unit basin area [M/L^2], mass per unit time [M/T], or mass per unit basin area per unit time [$M/L^2/T$]). The quantity Y_T for the Waikele watershed and subbasins within the watershed was determined using automated streamflow/sediment gages to monitor the suspended-sediment loads in the streams at the points where they exit the watershed or subbasin. The quantity Y_C was determined by measuring annual changes in sediment storage at selected locations on stream channels within the watershed and its subbasins. The yield from hillslopes in the watershed and subbasins was then determined by solving equation 1 for Y_H.

Data for this study were collected in the 2008, 2009, and 2010 water years (October 1, 2007, through September 30, 2010). The concept of the water year was established to avoid splitting the winter-spring wet season into two different years. The USGS uses a water year that begins on October 1 of the previous calendar year and ends on September 30. For example, the 2008 water year includes the period from October 1, 2007, to September 30, 2008. The standard USGS water year is consistent with the climate of most of the United States (Rantz and others, 1982b) including Hawai‘i. For brevity, water years in this report will be expressed by “WY” followed by the year; for example, water year 2008 will be expressed as “WY2008.”

Streamflow and Suspended-Sediment Loads

Streamflow and suspended-sediment loads were monitored at four locations using automated streamflow/sediment gages (figs. 2 and 5, table 1). The USGS National Water Information System (NWIS) database lists these gages as Kīpapa Stream near Wahiawa (16212800), Waikele Stream at Wheeler Field (16212601), Waikele Stream at Waipahu (16213000), and Mililani Storm Drain A (212604158012700). For brevity, these gages are referred to in this report as the Kīpapa, Wheeler, Waipahu, and Mililani gages, respectively.

The Waipahu gage integrates output from all areas in the watershed; data from this gage are an indicator of the Waikele watershed as a whole. The Wheeler, Kīpapa, and Mililani gages monitor subbasins within the Waikele watershed; these subbasins are independent of each other and their data are indicators of conditions in specific parts of the watershed. A fourth subbasin, referred to as the “Waipahu Exclusive” subbasin in this report, was computed by subtracting the data and the drainage areas of the Wheeler, Kīpapa, and Mililani subbasins from those of the Waipahu drainage basin. Data computed for this subbasin is an indicator of the conditions in the part of the watershed not encompassed by the Wheeler, Kīpapa, and Mililani subbasins (fig. 5).

The gages were equipped with water-level (stage) recorders, automated water samplers, and satellite telemetry. The gages were programmed to scan stage every 5 minutes, and under conditions when the stage remained below a predetermined threshold, the instantaneous stage was recorded at 15-minute intervals. Above the threshold, instantaneous stage was recorded at 5-minute intervals. The instantaneous stage readings were converted to instantaneous streamflow using a rating curve developed on the basis of periodic direct current-meter measurements made at various stages (Rantz and others, 1982a, 1982b). The instantaneous streamflow values are used in the computation of other statistics, such as the daily and annual mean streamflows. To allow comparison between basins, annual and study-period mean streamflows were divided by drainage area to compute runoff.

The gages were also equipped and maintained to collect suspended-sediment data in accordance with techniques described in Edwards and Glysson (1999). The gages were programmed to automatically collect water samples at 5-minute intervals when stage rose above specified triggering thresholds. The objective of the sampling was to assess suspended-sediment loads in the stream; therefore, the intakes of the automated samplers were positioned about 0.5 ft above the stream bottom to avoid sampling coarser bed sediment. Samples were also collected manually during various periods of flow to assess how suspended-sediment concentrations vary across the width of flow in the stream channel; these samples were used to convert the point concentrations measured by the gages to the average concentration across the width and depth of the channel. The samples were analyzed at the USGS Cascades Volcano Observatory for suspended-sediment

Table 1. Streamflow/sediment gages in the Waikele watershed, O‘ahu, Hawai‘i.

[Period of record may include partial water years. Data are from USGS National Water Information System (NWIS)]

Gage	Description	Gage number	Location (latitude, longitude)	Approximate elevation (feet above sea level)	Drainage area (square miles)	Period of record (water years)	
						Streamflow	Sediment
Wheeler	Upper part of watershed, in Wai‘anae Mountains	16212601	21° 28' 20.3", 158° 02' 40.1"	710	6.72	2008–2010	2008–2010
Kīpapa	Upper part of watershed, in Ko‘olau Mountains	16212800	21° 28' 01.6", 157° 57' 31.6"	690	4.28	1957–2004, 2008–2010	1973–1982, 2008–2010
Mililani	Urban area in central watershed	212604158012700	21° 25' 49.9", 158° 01' 18.6"	540	0.56	2008–2010	2008–2010
Waipahu	Represents entire watershed	16213000	21° 23' 00.5", 158° 00' 39.3"	less than 10	45.14	1951–2010	1972–1993, 2008–2010

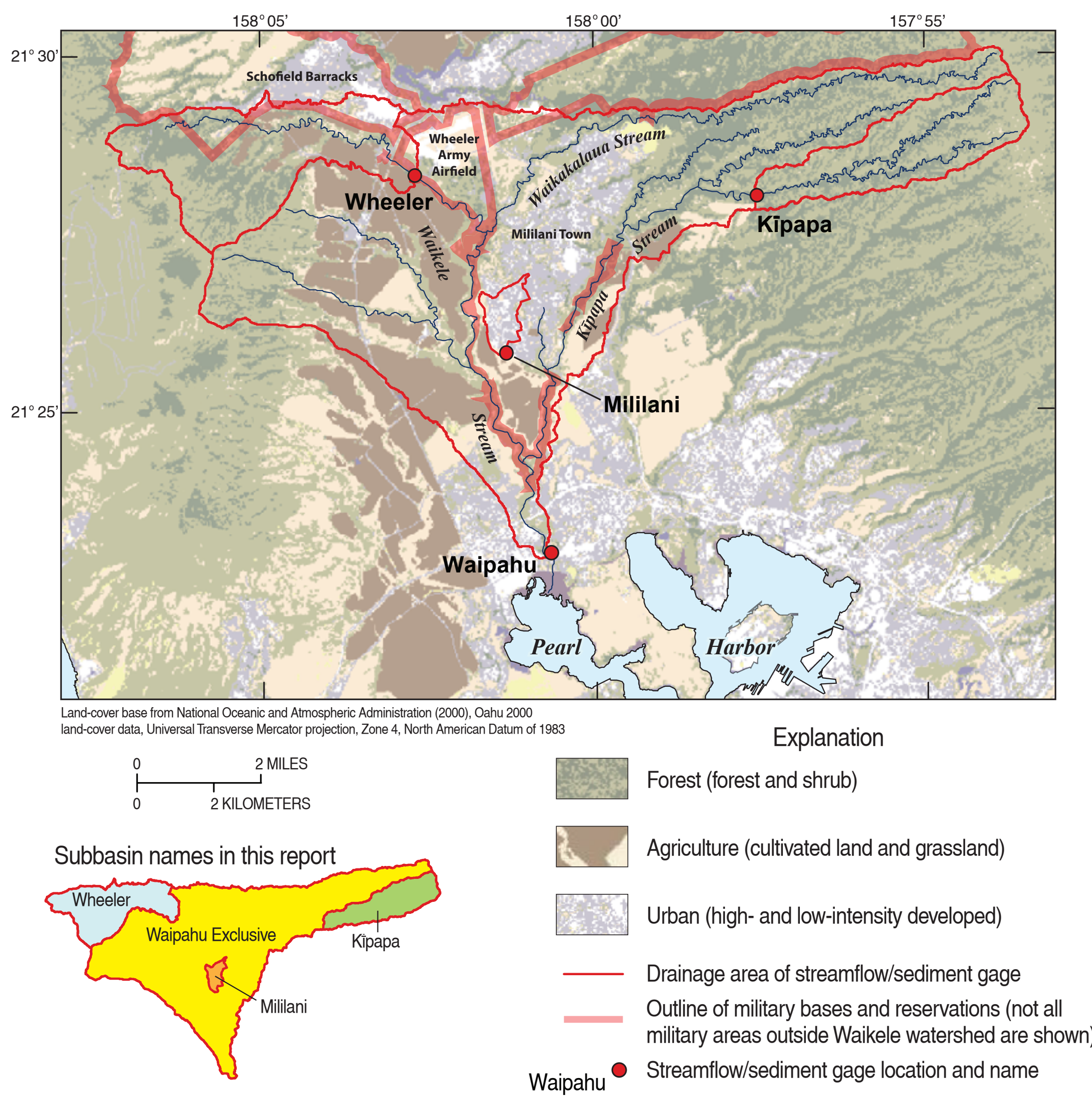


Figure 5. Map of streamflow/sediment gages, subbasin outlines, and land use in the Waikele watershed, O‘ahu, Hawai‘i. Land use (forest, agriculture, and urban) interpreted from land-cover categories (shown in parentheses) in National Oceanic and Atmospheric Administration (2000). Outline of military bases and reservations are from the U.S. Geological Survey (2003); only military areas that are within or partly within the Waikele watershed are shown.

concentration. Daily, monthly, and annual suspended-sediment loads were computed from the streamflow and suspended-sediment-concentration data using techniques described by Porterfield (1972) and the computer program GCLAS (Koltun and others, 2006).

Changes in Channel Sediment Storage

Channel sediment yield in the Waikele watershed was determined by measuring changes in channel storage. The changes in channel storage were computed from annual surveys of stream-channel cross-sectional area. The surveys were scheduled to correspond approximately with the end of each water year. Changes in channel cross-sectional area from one water year to the next were interpreted as changes in channel sediment storage, which in turn were interpreted as channel sediment yield. The purpose of the cross-section surveys was to assess changes in channel-bed storage only; bank erosion was not assessed in this study.

Twenty-three to twenty-seven cross sections in eight cross-section groups (two to six cross sections per group) were measured each year (fig. 6). (The Mililani subbasin was excluded from this survey because it has a maintained concrete-lined channel assumed to have negligible sediment yield.) Cross-section group locations were selected to be representative of the channel morphology in nearby stream reaches; cross-section locations were selected to be representative of the depositional environments (for example, pools and riffles) at the group location. Cross sections within a group were separated by a distance equal to or greater than the average channel width. To facilitate repeated annual measurements over the 3-year period of this study, group locations were determined using a global positioning system (GPS) and cross-section locations were marked with monuments. The azimuth of the line of each cross section was also determined in case monuments were lost or destroyed.

One monument in each cross section was used as a vertical and horizontal reference datum. A measuring tape was stretched between the cross-section monuments to measure horizontal distances relative to the reference datum (fig. 7). A digital automatic surveying level and rod were used to measure the elevation of the channel bottom relative to the reference datum. Elevation measurements were made at selected points along the cross-section line. A minimum of 20 points were measured per cross section per visit; more points were measured in channels that were wide or had complex topography. The area of each cross section was computed by

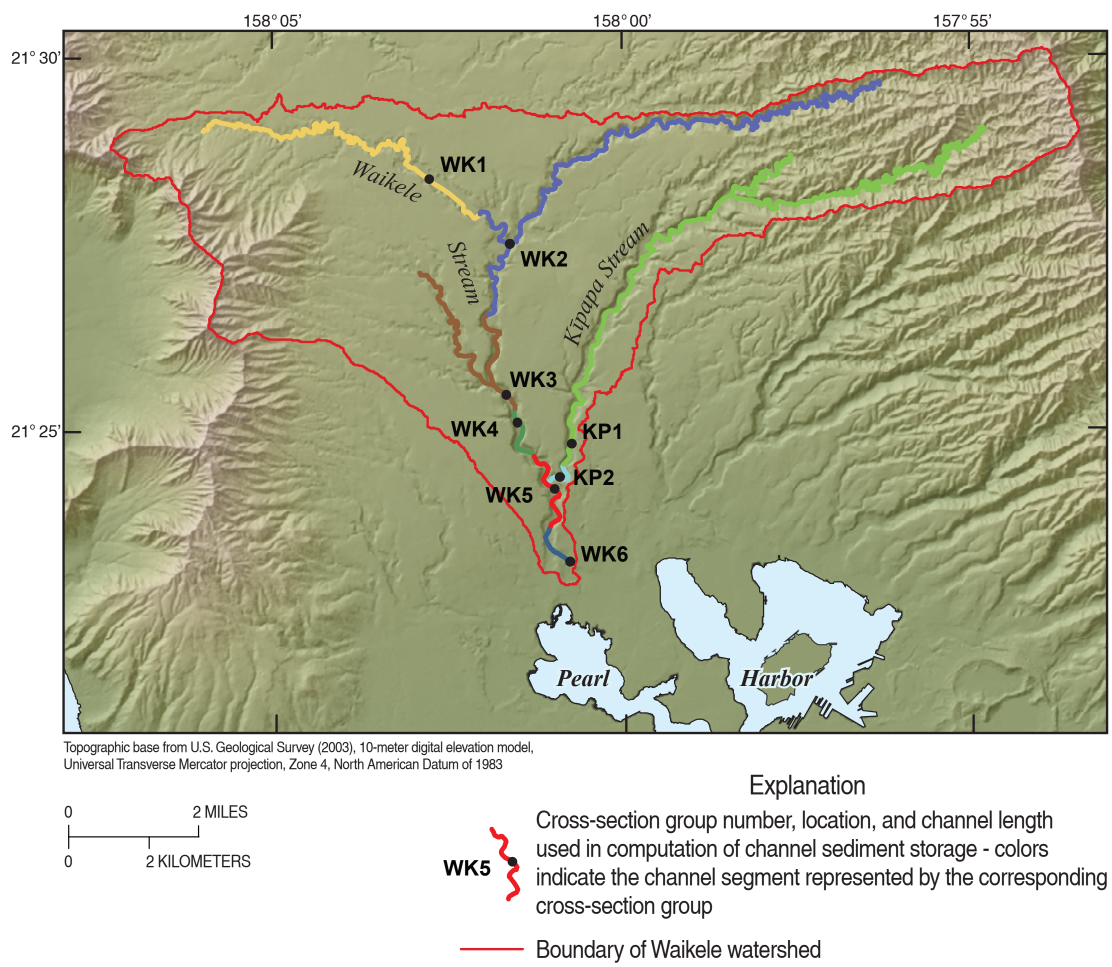


Figure 6. Map of channel lengths and cross-section groups used to compute change in sediment storage in channels in the Waikele watershed, O‘ahu, Hawai‘i.

summing the trapezoidal subareas defined by the horizontal distance between adjacent points and their elevation relative to the reference point. For each cross section, the difference between the cross-sectional area for a given water year and the previous water year was computed. The differences for all cross sections in a group were then averaged to determine the annual mean change in cross-sectional area.

If a monument was destroyed by channel erosion between annual measurements, a new monument was established along the original cross-section line using azimuth data recorded when the cross section was originally installed (fig. 8). Because erosion widened the channel, the new monument was placed farther from the intact monument than the original monument had been. The volume of erosion was estimated by extrapolating the pre-erosion profile to the new monument location and computing the cross sectional area between the monuments, then comparing that area to the area of the post-erosion profile.

In some cases, erosion caused the loss of both monuments of a cross section, thus making it impossible to measure the area change for that cross section for that year. In these cases, a new cross section was established near the old cross section so that changes in subsequent years could be measured. Even with such losses, however, at least two cross sections were measured per group per year, except in WY2009 when all sections of WK6, the lowermost group, were destroyed. To compute changes in channel sediment volume for WY2009, the cross sectional change from the next upstream group (WK5) was used to estimate the changes for the reach that would have been represented by WK6. Replacement cross sections were also established at WK6 so that changes in WY2010 could be measured.

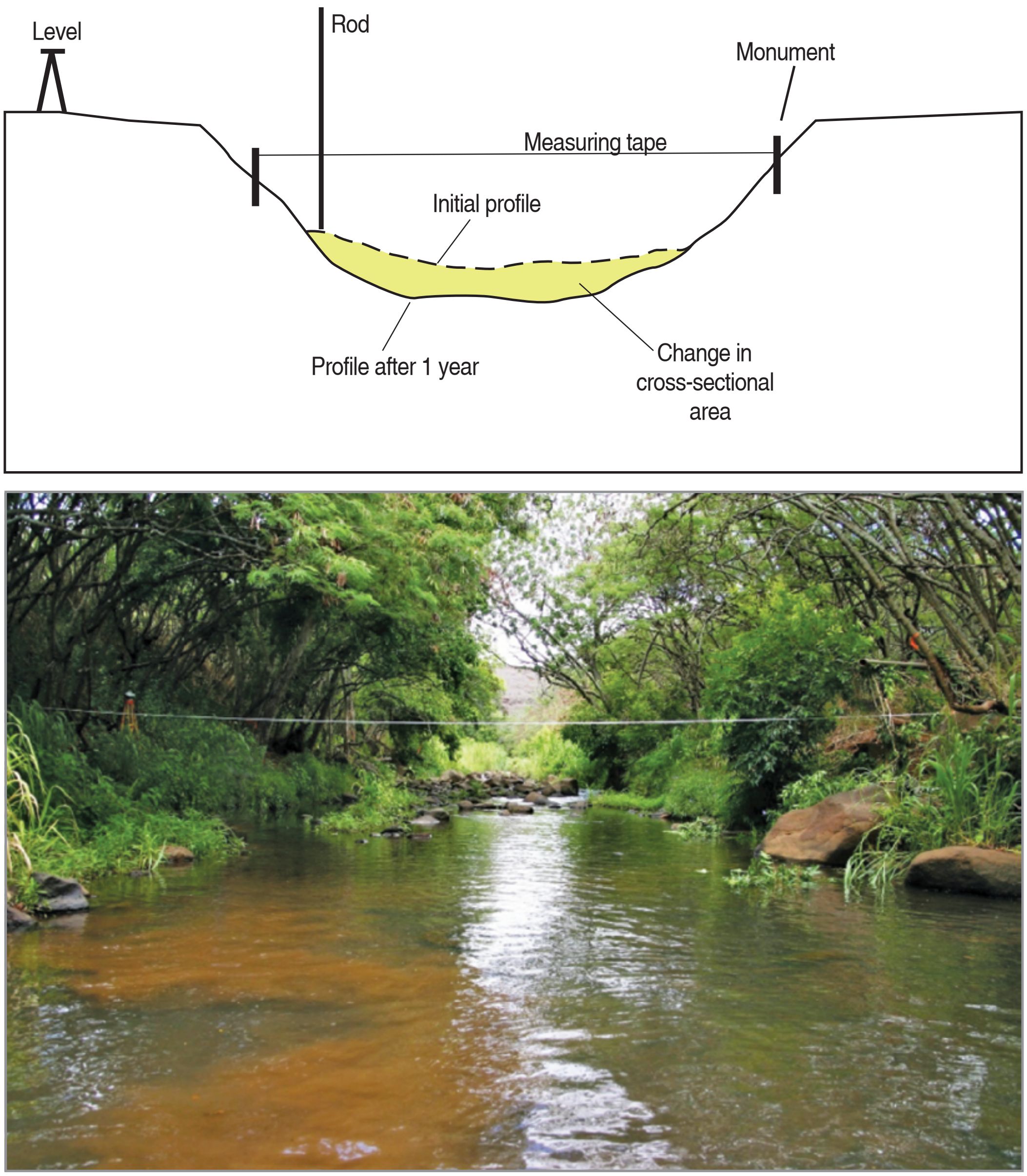


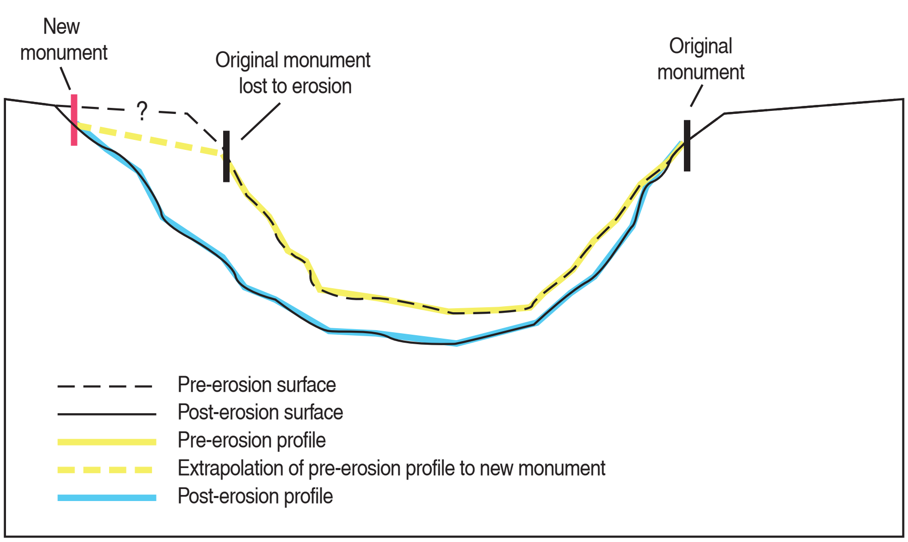
Figure 7. Diagram showing measurement of change in channel cross section to determine change in sediment storage. Photograph shows one of the six cross sections in group WK5. Photograph taken August 1, 2007.

Estimating Change in Channel Suspended-Sediment Storage—The cross sections provide data for estimating the volumetric change in channel sediment storage, but the volume of sediments stored in the channels of Waikele Stream and its tributaries typically includes clasts ranging from boulders to clay; only the finer fraction of this sediment can be transported as suspended load. Most of the suspended load consists of silt and clay (particles less than 0.063 mm), but may include some sand depending on energy of the streamflow. To facilitate comparison between the channel-storage measurements and the suspended-sediment loads measured by the gages, the proportion of the channel-sediment volume composed of clay, silt, and sand was estimated using a modified version of the Wolman (1954) pebble count, in addition to sampling and sieving. For the pebble counts, 4 to 20 evenly spaced transects across the channel were set up at each of the cross-section groups shown in figure 6. At each transect, a measuring tape was stretched across the channel and a description of the clasts (using the Wentworth [1922] scale) at points every foot along the tape was recorded. A minimum of 100 points were counted in each cross-section group. If the clast at a point was larger than a pebble, the proportion of suspended sediment was assumed to be zero. If the clast was a pebble or smaller, a sediment sample was taken to determine, by wet-sieve analysis in the laboratory, the proportion (by weight) of the sample consisting of silt and clay. The weight proportion consisting of sand (grains between 0.063 and 2 mm) was also determined from the sieve analysis.

Table 2. Percentage of silt and clay in the samples selected for grain-size analysis from the suspended-sediment samples collected by the streamflow/sediment gages in the Waikele watershed, O‘ahu, Hawai‘i, during the period of this study (water years 2008 to 2010).

[ft^3/s; cubic feet per second; mg/L, milligrams per liter]

Gage	Date	Time	Stream-flow (ft^3/s)	Suspended-sediment concentration (mg/L)	Silt and clay (percent)
Wheeler	2/7/08	1600	184	1,365	95.0
Wheeler	5/21/08	1610	62	499	92.0
Wheeler	11/15/08	0045	105	1,310	68.2
Wheeler	12/11/08	0635	1,560	15,077	85.6
Wheeler	3/17/10	1745	53	1,261	95.8
Kīpapa	11/4/07	0150	105	1,439	98.5
Kīpapa	2/2/08	1030	227	468	96.7
Kīpapa	2/6/08	1915	561	1,967	97.6
Kīpapa	10/15/08	1030	146	192	82.5
Kīpapa	12/28/08	0730	82	263	96.7
Kīpapa	8/12/09	0815	131	78	91.2
Kīpapa	12/11/08	0645	915	3,761	94.3
Waipahu	11/4/07	0345	1,230	1,154	82.2
Waipahu	4/7/10	0000	793	1,187	69.8
Waipahu	4/7/10	0937	598	299	98.2
				Average	89.6



Estimating change when one monument of a cross section has been lost due to erosion

1. New monument established along the original cross-section line and post-erosion profile is measured (blue line)
2. Pre-erosion profile (solid yellow line) is extrapolated to the new monument location (dashed yellow line)
3. Difference between the area of post-erosion profile and the area of the pre-erosion profile (including extrapolated area) is the change in cross sectional area due to erosion.

Figure 8. Diagram showing measurement of change in channel cross section when one monument is destroyed.

Comparing data on changes in channel storage to suspended-sediment loads measured at the gages is complicated by the nonconservative nature of fluvial transport of sand—sand can go in and out of suspension depending on flow conditions. Thus, even knowing the proportions of sand, silt, and clay in the channel sediments, there is no way to precisely convert the change-in-channel-storage data to an equivalent suspended-sediment yield for comparison to the gage data. However, grain-size analyses were done on some of the suspended-sediment samples from the gages, and these analyses indicate that in general, sand constitutes only a small fraction of the suspended load. During this study, grain size was analyzed for 15 suspended-sediment samples from the Wheeler, Kīpapa, and Waipahu streamflow/sediment gages (Mililani is excluded for reasons previously described). The average silt-and-clay content of these samples was about 90 percent (table 2). On the basis of this data, it is assumed for the purposes of this study that the change in silt-and-clay storage estimated by the channel cross sections is a close approximation of the channel yield to the suspended-sediment budget.

Sediment-density data were also collected and used to convert the volumetric results from the channel cross sections to mass. Six channel bed-sediment samples were analyzed for bulk density. Relatively undisturbed samples of known volume were collected by inserting a metal tube of known volume into the bed sediments. Sample dry weights determined in the laboratory were divided by the volume of the sampling cylinder to obtain bulk density. The average bulk density of these samples was applied to all volumetric changes in channel storage to compute mass values.

For each cross-section group, the annual change in silt-and-clay mass per unit length of channel, ΔM [M/L], was computed by:

$$\Delta M = \rho \overline{\Delta A} \cdot P \qquad \text{(eq. 2)}$$

where ρ is the average bulk density of channel-bed sediments [M/L^3], $\overline{\Delta A}$ is the annual average change in cross-sectional area in the group [L^2], and P is the volumetric fraction of the channel bed composed of silt and clay. For $\overline{\Delta A}$ (and therefore ΔM), negative values indicate reduction in channel sediment storage (erosion).

Extrapolating to Reaches between Cross-Section Groups —The annual values of ΔM from the cross-section groups measured in this study were extrapolated to reaches between the groups to estimate the annual suspended-sediment yields from all channels in the Waikele watershed. For a given cross-section group, ΔM was extrapolated over one-half the length of channel between adjacent groups in both the upstream and downstream directions (fig. 6). For the uppermost groups WK1 and KP1, the upstream extrapolation of ΔM was applied to channels and tributaries having a Shreve (1967) stream order of three or higher as determined from stream channels shown on the USGS 1:24,000-scale topographic maps (U.S. Geological Survey, 2006). For the gulches to the west of WK3, the value of ΔM for group WK3 was extrapolated to channels having a stream order of three or higher. First- and second-order reaches were excluded because it was assumed that sediment volumes are insignificant in the highest, steepest channels of the watershed.

Computing Channel Suspended-Sediment Yield from Each Subbasin —The channel-storage data were merged with the drainage-basin boundaries using a Geographic Information System (GIS) program to compute the length of channel (L) in each subbasin corresponding with each value of ΔM (as determined from the extrapolation). The change in silt-and-clay storage for channels within a given subbasin, ΔS [M], was then computed by summing the products of ΔM times L for all cross-section groups (i) in or extrapolated into the subbasin:

$$\Delta S = \Sigma_{i=1}^{i=n} (\Delta M_i = \times L_i), \qquad \text{(eq. 3)}$$

where n is the number of cross-section groups in the subbasin. Negative values of ΔS indicate reduction in channel storage (erosion).

Suspended-Sediment Budget

The suspended-sediment budget is a mass balance of the sources and sinks of suspended sediments in the watershed and its subbasins; equation 1 is a simple suspended-sediment budget. The quantity ΔS is a measure of the yield of silt and clay from channels within the subbasin (Y_C in equation 1), but because negative values of ΔS indicate erosion, the channel yield is opposite in sign:

$$Y_C = -\Delta S \qquad \text{(eq. 4)}$$

Substituting into equation 1 and solving for Y_H gives:

$$Y_H = Y_T + \Delta S \qquad \text{(eq. 5)}$$

Whereas Y_C is determined from the change in channel storage and Y_T is equivalent to the load measured at the gage, equation 5 can be used to compute the yield from hillslopes in the subbasin (Y_H).

Results

Daily mean streamflow and suspended-sediment data from the gages in this study are stored in the USGS NWIS database. The data are public domain and available through the NWIS website (*http://waterdata.usgs.gov/nwis*). Summaries of the streamflow and suspended-sediment data as well as the data from the channel-storage monitoring are presented in the following discussion.

Data from Streamflow/Sediment Gages

Streamflow During Study Period—Streamflow from the Waipahu gage characterizes streamflow from the Waikele watershed during the period of this study. Streamflow at the Waipahu gage averaged 33 ft^3/s and daily mean streamflow ranged from 9.4 to 4,270 ft^3/s during the study period (table 3). Instantaneous streamflow ranged from 8.4 to 22,600 ft^3/s during the study period (table 4). The hydrograph from this gage shows storm-flow peaks superimposed on persistent base flow of about 9 to 13 ft^3/s (fig. 9,

Table 3. Summary of streamflow data from the Waikele watershed, Oʻahu, Hawaiʻi, during the period of this study (water years 2008 to 2010).

[ft^3/s; cubic feet per second; $ft^3/s/mi^2$, cubic feet per second per square mile; —, not applicable]

Water year	Highest daily mean streamflow: Value (ft^3/s)	Highest daily mean streamflow: Date	Highest daily mean streamflow: Relative to water year (by volume)	Highest daily mean streamflow: Relative to study period (by volume)	Lowest daily mean streamflow (ft^3/s)	Annual mean streamflow (ft^3/s)	Runoff ($ft^3/s/mi^2$)
Wheeler gage/subbasin							
2008	80	11/4/07	39%	9%	0.00	0.56	0.08
2009	384	12/11/08	58%	42%	0.00	1.8	0.27
2010	6.4	3/17/10	12%	1%	0.00	0.15	0.02
				Study-period average		0.84	0.12
Kīpapa gage/subbasin							
2008	306	11/4/07	11%	4%	0.00	7.6	1.8
2009	372	12/11/08	12%	4%	0.00	8.4	2.0
2010	151	11/14/09	6%	2%	0.05	6.9	1.6
				Study-period average		7.6	1.8
Mililani gage/subbasin							
2008	5.3	11/4/07	11%	4%	0.00	0.13	0.23
2009	5.9	12/11/08	11%	4%	0.00	0.15	0.27
2010	1.7	1/29/10	5%	1%	0.00	0.09	0.16
				Study-period average		0.12	0.22
Waipahu Exclusive subbasin							
2008	—	—	—	—	—	25	0.74
2009	—	—	—	—	—	30	0.89
2010	—	—	—	—	—	17	0.51
				Study-period average		24	0.71
Entire Watershed (represented by Waipahu gage/drainage basin)							
2008	1,420	11/4/07	12%	4%	13	34	0.75
2009	4,270	12/11/08	29%	12%	11	41	0.91
2010	565	4/7/10	6%	2%	9.4	24	0.53
				Study-period average		33	0.73

table 3). The persistent base flow at this site is consistent with groundwater discharge from the Pearl Harbor Springs.

Streamflow data from the subbasins reflect the different climates, hydrogeologic settings, and land uses in different parts of the watershed (fig. 5). Runoff for the study period was highest from the Kīpapa subbasin (1.8 $ft^3/s/mi^2$), which is consistent with its location in the wettest part of the watershed (table 3). Runoff was lowest from the Wheeler subbasin (0.12 $ft^3/s/mi^2$), which is in the driest part of the watershed. Runoff from the Mililani subbasin (0.22 $ft^3/s/mi^2$) was intermediate between those of the Wheeler and Kīpapa subbasins, probably because of differences in rainfall and factors related to urbanization. Runoff from the Waipahu Exclusive subbasin (0.71 $ft^3/s/mi^2$), which encompasses a wide variety of climate and land cover, was also intermediate between the runoff values for Wheeler and Kīpapa subbasins.

Streamflow data from the Wheeler, Kīpapa, and Mililani gages included zero-flow days (table 3), which indicates that stream reaches at the gage sites are intermittent. The hydrograph from the Wheeler gage has few discharge peaks separated by numerous zero-flow days; zero-flow days constituted 86 percent of the daily-mean-streamflow record from this gage. In contrast, the hydrograph from the Kīpapa gage is characterized by frequent discharge peaks with few days of zero flow; zero-flow days constituted only 2 percent of the record at this gage (fig. 9).

The daily-mean-streamflow record from the Mililani gage has few zero-flow days (5 percent), even though the Mililani subbasin is in a relatively dry part of the watershed (fig. 2). The dry-season hydrograph of instantaneous streamflow at the Mililani gage shows peaks of similar magnitude that occur regularly at about the same time of day (fig. 10). The regularity of these dry-season streamflows suggests an artificial source of water, such as automated landscape irrigation.

A seasonal pattern coinciding with the typical pattern of wet and dry seasons in Hawaiʻi is evident in the hydrographs of all gages during the study period (fig. 9). In general, streamflow peaks are higher and more frequent in the earlier part of the water year, and low-flow or zero-flow days are more common in the later part of the water year. The

Table 4. Number of suspended-sediment samples collected and ranges of streamflows during the period of this study (water years 2008 to 2010) from streamflow/sediment gages in the Waikele watershed, Oʻahu, Hawaiʻi.

[ft^3/s; cubic feet per second; —, not applicable; <, less than]

Water year	Range of streamflow in water year (ft^3/s)	Automated samples		Manual samples	
		Number of samples	Range of streamflow (ft^3/s)	Number of samples	Range of streamflow (ft^3/s)
Wheeler					
2008	0–498	129	2.1–494	0	—
2009	0–1,750	53	25–1,730	0	—
2010	0–200	33	3.9–122	0	—
Total		215		0	
Kīpapa					
2008	0–1,480	217	0.02–1,320	4	0.10–66
2009	0–2,930	200	< 0.01–2,730	3	6.5–21
2010	0.03–979	153	0.30–711	1	2.4
Total		570		8	
Mililani					
2008	0–203	87	0.05–73	0	—
2009	0–115	116	0.02–104	0	—
2010	0–54	67	0.07–22	0	—
Total		270		0	
Waipahu					
2008	10–6,080	309	14–4,660	1	171
2009	9.6–22,600	140	11–388	2	14–87
2010	8.4–1,400	118	4.0–1,230	5	16–572
Total		567		8	

seasonal pattern is more distinct in WY2008 and WY2009, and less distinct in WY2010.

At all gages, annual mean streamflow was highest in WY2009, lowest in WY2010, and intermediate in WY2008 (table 3). The interannual variation corresponds with variations in the frequency and magnitude of storm-flow peaks from one year to the next (fig. 9). In some cases, single storm events accounted for a substantial part of the total streamflow volume for the water year and the study period. For example, the highest daily mean flow at all gages during the study period occurred during a major storm on December 11, 2008; this storm flow contributed substantially to the total volume of water discharged in WY2009, particularly at the Wheeler and Waipahu gages (table 3). The storm of December 11, 2008, is discussed in more detail below because it caused record high streamflows in parts of the watershed. Other storms also contributed substantially to the interannual variation in streamflows. For example, at all gages, the second highest daily value during the study period occurred during a storm on November 4, 2007; flows from this storm contributed a substantial fraction of the total streamflow in WY2008, which had the second highest annual mean of the three water years in this study.

Suspended-Sediment Loads During Study Period—During the period of this study, the automated water samplers in the gages in the Waikele watershed collected 1,622 samples when flows ranged from 0 to 4,660 ft^3/s (table 4). Eight samples each from the Kīpapa and Waipahu gage sites were also collected manually near the gages to adjust the point concentrations measured by the gages to the average concentration across the width and depth of the channel; these samples were collected during flows ranging from 0.10 to 66 ft^3/s at the Kīpapa gage, and 14 to 572 ft^3/s at the Waipahu gage. The ratio of the concentrations from the manual samples to the concentrations in concurrent automated samples (known as “box coefficients”) averaged 0.84 for Kīpapa and 1.09 for Waipahu.

Suspended-sediment yield from the Waikele watershed, as indicated by the suspended-sediment load at the Waipahu gage, averaged 82,500 tons/yr during the study period (table 5). Variations in the annual suspended-sediment load followed a pattern similar to streamflow, with highest load in WY2009

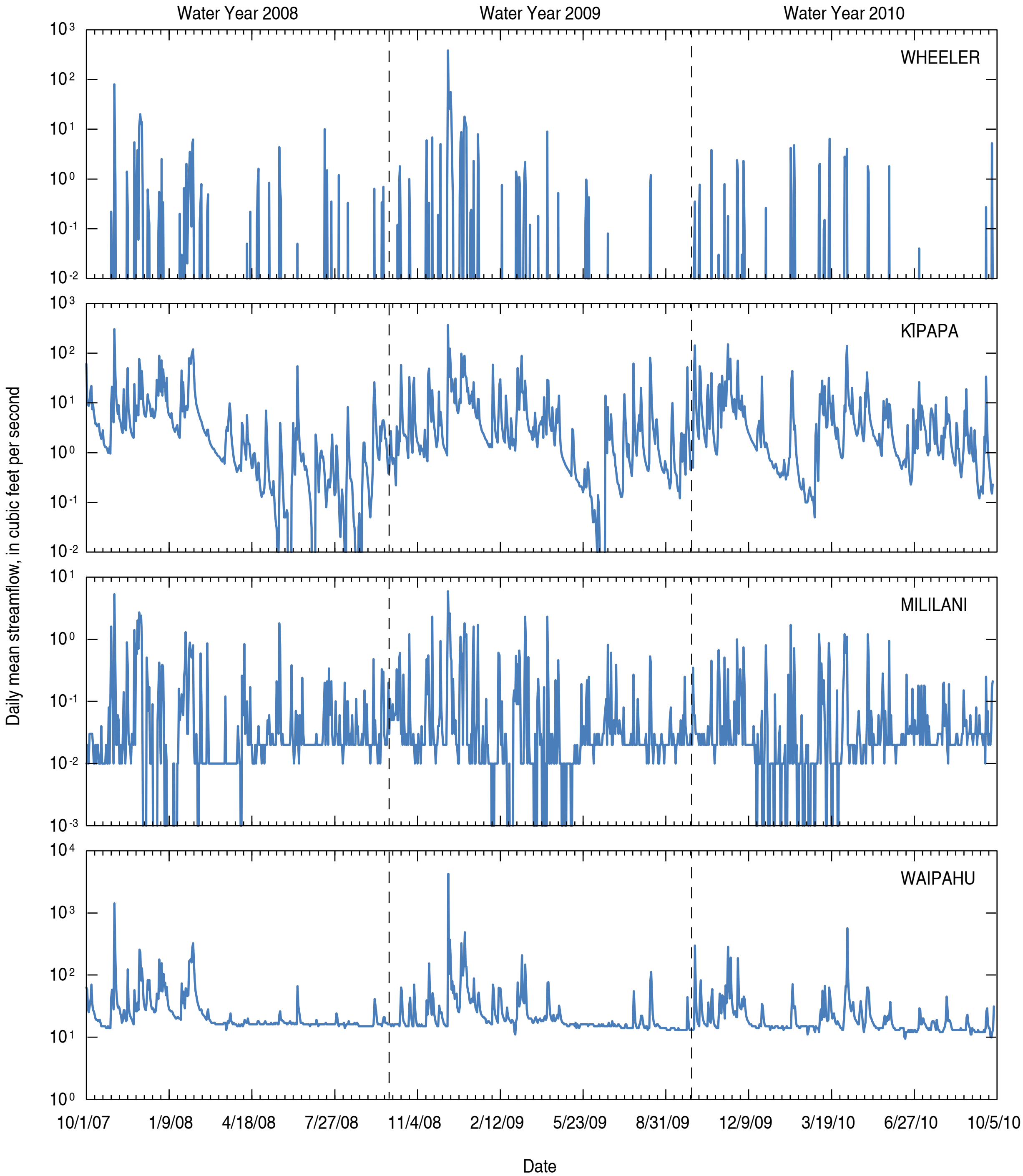


Figure 9. Graphs showing daily mean streamflow from gages in the Waikele watershed, O‘ahu, Hawai‘i, during the period of this study (water years 2008 to 2010).

Table 5. Summary of suspended-sediment data from gages and subbasins in the Waikele watershed, O'ahu, Hawai'i, during the period of this study (water years 2008 to 2010).

[Normalized yield is annual load (or study period average load) divided by area of drainage basin; tons/yr/mi^2, tons per year per square mile; —, not applicable]

Water year	Highest daily load at gage				Lowest daily load at gage (tons)	Annual load (tons)	Normalized yield (tons/yr/mi^2)
	Value (tons)	Date	Relative to water year	Relative to study period			
Wheeler gage/subbasin							
2008	481	11/4/07	74%	6%	0.0	650	97
2009	6,600	12/11/08	93%	85%	0.0	7,070	1,050
2010	33	3/17/10	38%	0%	0.0	88	13
				Study-period average		2,600	387
Kīpapa gage/subbasin							
2008	755	11/14/07	52%	15%	0.0	1,460	341
2009	2,350	12/11/08	81%	46%	0.0	2,910	680
2010	221	10/5/09	33%	4%	0.0	680	159
				Study-period average		1,690	395
Mililani gage/subbasin							
2008	3.6	11/4/07	22%	9%	0.0	16	29
2009	4.1	12/11/08	26%	10%	0.0	16	29
2010	1.1	1/29/10	12%	3%	0.0	9.4	17
				Study-period average		14	25
Waipahu Exclusive subbasin							
2008	—	—	—	—	—	11,800	351
2009	—	—	—	—	—	220,000	6,550
2010	—	—	—	—	—	2,710	81
				Study-period average		78,200	2,330
Entire Waikele watershed (represented by Waipahu gage/drainage basin)							
2008	10,500	11/4/07	75%	4%	0.24	14,000	310
2009	227,000	12/11/08	99%	92%	0.08	230,000	5,100
2010	1,430	4/7/10	41%	1%	0.09	3,490	77
				Study-period average		82,500	1,830

(230,000 tons), lowest load in WY2010 (3,490 tons), and an intermediate load in WY2008 (14,000 tons). Daily suspended-sediment loads ranged from 0.08 tons to 227,000 tons during the study period.

Peaks in daily suspended-sediment loads correspond with peaks in daily mean streamflow (figs. 9 and 11). At the Wheeler, Kīpapa, and Mililani gages, days of zero suspended-sediment load correspond with days of zero streamflow. At the Waipahu gage, where base flow from groundwater discharge persists, the daily suspended-sediment load declined to as low as 0.08 tons (table 5). The graphs of daily suspended-sediment load (fig. 11) show a seasonal pattern in which peaks are higher and more frequent in the earlier part of the water year, which is similar to the seasonal pattern seen in streamflow (fig. 9).

The normalized suspended-sediment yield for the study period from the Waipahu Exclusive subbasin (2,330 tons/yr/mi^2) was nearly six times greater than the normalized suspended-sediment yield from any other subbasin in the study (table 5). The Kīpapa and Wheeler subbasins had similar normalized suspended-sediment yields of about 390 tons/yr/mi^2 during the study period. The normalized suspended-sediment yield of the Mililani gage (25 tons/yr/mi^2) was much smaller than any other gage. The normalized suspended-sediment yield for the Waikele watershed as a whole during the study period was 1,830 tons/yr/mi^2.

Storm of December 11, 2008—The period of this study included a storm that caused heavy rains and significant flooding in the Waikele watershed on December 11, 2008. At the Waipahu gage, the peak flow during the storm (22,600 ft^3/s) exceeded the previous highest peak (13,000 ft^3/s) in the gage's 59-yr period of record. Data from other gages indicate, however, that the storm did not affect the watershed uniformly. At the Kīpapa gage, the peak flow during the storm (2,930 ft^3/s) was substantially below the highest flow on record (6,370 ft^3/s) in the gage's 51-yr history.

Flood-frequency analyses were used to assess the magnitude of streamflows generated by the storm of December 11, 2008, relative to other streamflow peaks in the record of the Kīpapa and Waipahu gages (Flynn and others, 2006). The analyses were consistent with the methods used to compute station peak-flow values described by

Oki and others (2010) and included data from the entire periods of record for each gage. The peak instantaneous flow at the Kīpapa gage generated during the storm had an annual exceedance probability of about 20 percent, which indicates a recurrence interval of 5 years. In contrast, the peak instantaneous streamflow generated by the storm at the Waipahu gage had an annual exceedance probability between 1 and 2 percent, which indicates a recurrence interval between 50 and 100 years.

For some gages in the watershed, the volume of water discharged during the December 11, 2008, storm constituted a large fraction of the total water discharged in WY2009 and the study period. At the Wheeler gage, the volume of stream water discharged during the single day of the storm accounted for 58 percent of the total streamflow volume in WY2009 and 42 percent of the total volume during the study period (table 3). Streamflow during the day of the storm also accounted for a substantial fraction of the streamflow volume discharged at the Waipahu gage in WY2009 (29 percent) and in the study period (12 percent). The effect of the storm was smaller at the Kīpapa and Mililani gages—flow during the day of the storm accounted for 11 to 12 percent of the streamflow volume discharged in WY2009 and 4 percent of the streamflow volume discharged in the study period. The daily mean streamflow during the storm at these gages was also not much higher than the highest daily mean streamflow in the previous year, WY2008 (table 3).

The highest annual suspended-sediment yield and normalized suspended-sediment yield during the study period from the Wheeler and Kīpapa subbasins, as well as from the Waikele watershed as a whole, was in WY2009, which included the storm of December 11, 2008 (table 5). The highest daily load recorded at these gages during the study period corresponded to the storm of December 11, 2008, and the single day of the storm constituted 81 to 99 percent of the WY2009 load, and 46 to 92 percent of the total suspended-sediment load measured during the study period. The precise load at the Waipahu gage on the day of the storm is uncertain because the flood destroyed the samples from the autosampler and the concentration at the flow peak was estimated on the basis of the relation between streamflow and concentration. Even with the uncertainty, the data indicate that the storm of December 11, 2008, caused the transport of a large amount of sediment from most areas of the watershed. In contrast, the annual suspended-sediment yield from the Mililani subbasin for WY2009 was not substantially different from WY2008, and the day of the storm accounted for a smaller portion of the WY2009 load (26 percent) and study-period load (10 percent).

Changes in Channel Storage

The six bed-sediment samples collected from Waikele Stream and its tributaries for bulk density analysis included grain sizes from clay to pebbles. Bulk densities ranged from 0.75 to 1.26 g/cm^3, and averaged 1.09 g/cm^3 with a standard deviation of 0.20 g/cm^3 (table 6). Because the bulk density analysis does not include boulders, which are common in the channel-bed sediment in the Waikele watershed, the average probably underestimates the bulk density of bed sediments. However, the average is probably a close estimate of the bulk density of the finer particles that tend to become suspended.

Table 6. Bulk density of bed-sediment samples from Waikele watershed, Oʻahu, Hawaiʻi.

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

Predominant texture	Date collected	Bulk density (g/cm^3)
Mostly coarse sand to small pebbles	9/7/10	1.24
Coarse sand to pebbles	9/7/10	0.96
Gravel to coarse sand, few pebbles	9/1/10	1.18
Mostly sand, some gravel	9/10/10	0.75
Mud to pebbles	9/1/10	1.17
Sand and pebbles	9/2/10	1.26
	Average	1.09
	Standard deviation	0.20

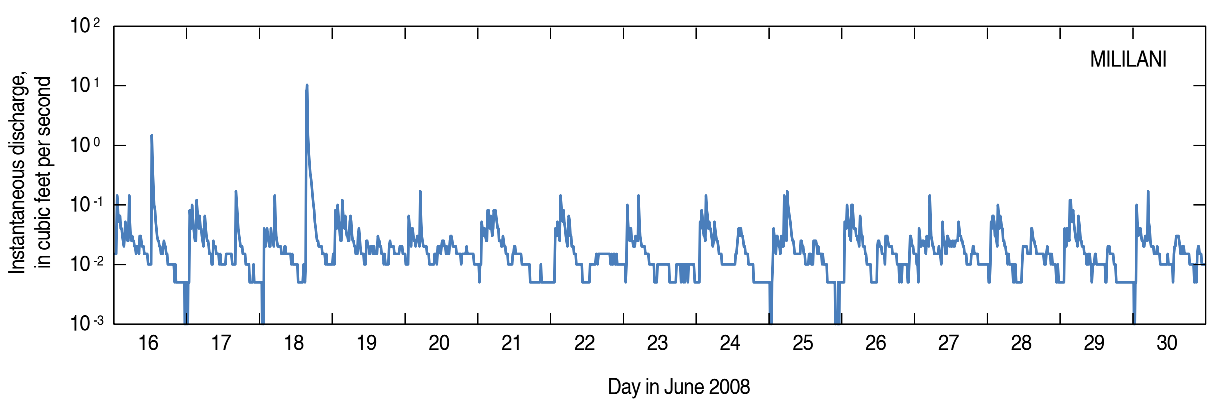


Figure 10. Graph showing instantaneous streamflow at the Mililani gage, Waikele watershed, Oʻahu, Hawaiʻi, during a dry period (June 16–30, 2008).

Table 7. Grain-size percentages for streambed sediments in the Waikele watershed, Oʻahu, Hawaiʻi.

[mm, millimeters; >, greater than; <, less than, ≤, less than or equal to]

Cross-section group	Number of points counted	Number of sieved samples	Estimated percentage of sediment volume		
			Coarser than sand (>2 mm)	Sand (>0.063 to 2 mm)	Silt and clay (≤0.063 mm)
KP1	174	54	82.8	15.4	1.8
KP2	198	14	98.4	1.6	0.1
WK1	176	86	78.1	18.5	3.4
WK2	143	97	69.1	22.8	8.1
WK3	127	27	94.6	5.1	0.4
WK4	132	31	90.8	8.0	1.2
WK5	277	72	90.6	8.3	1.0
WK6	159	91	72.9	24.1	3.0

Table 8. Estimated changes in channel storage of silt and clay at cross-section groups, Waikele watershed, Oʻahu, Hawaiʻi.

[Negative change indicates erosion. ft^2, square feet; ton/mi, tons per mile; WY, water year; —, not measured because monuments were destroyed]

Cross-section group	Percentage of streambed composed of silt and clay	Change in channel cross-section area (ft^2)			Change in mass of silt and clay (ton/mi)		
		WY2008	WY2009	WY2010	WY2008	WY2009	WY2010
WK1	3.43	-2.19	9.77	-0.94	-13.5	60.3	-5.8
WK2	8.08	0.00	-5.84	-2.21	0.04	-84.8	-32.2
WK3	0.39	0.21	-58.70	0.37	0.15	-41	0.26
WK4	1.16	-0.06	-37.71	1.12	-0.12	-78.7	2.33
WK5	1.05	-1.24	-70.77	3.32	-2.34	-134	6.27
WK6	3.03	17.13	—	5.38	93.4	—	29.3
KP1	1.82	-0.51	2.53	-6.54	-1.7	8.31	-21.4
KP2	0.06	-0.28	-22.74	0.68	-0.03	-2	0.07

The average is similar to the average (0.89 g/cm^3) reported by Hill and others (1998) for bed sediments in North Hālawa Stream, Oʻahu.

The results of the grain-size analyses (pebble counts and sieving) indicate that channel-bottom sediments in the Waikele watershed are predominantly coarse. Table 7 shows that 69.1 to 98.4 percent of the volume of sediment in the channels at the cross-section sites were coarser than sand. Silt and clay constituted only 0.1 to 8.1 percent of the volume of channel-bottom sediment at the sites of the cross-section groups. The average proportion of silt and clay for the eight cross-section groups was 2.4 percent. These results indicate that only a small fraction of the volume of bed sediments are fine enough to be transported as suspended load in the stream. Hill and others (1998) reported a similar proportion of silt and clay (0.1 to 11.4 percent, with a mean of 1.9 percent) for bed sediments in North Hālawa Stream.

The average bulk density (1.09 g/cm^3 or 68.04 lb/ft^3) from table 6 and grain-size data from table 7 were used with the measured changes in cross-sectional areas to compute the changes in silt-and-clay mass per mile of stream channel at the eight cross-section groups in this study (table 8). In this computation, negative change indicates a reduction in channel storage (erosion) and positive change indicates an increase in channel storage (deposition).

In WY2008, the greatest reduction in silt-and-clay storage (–13.5 tons per mile) was at the uppermost cross-section group, WK1, and the greatest increase (93.4 tons per mile) occurred at the lowermost group, WK6 (table 8). The remaining groups showed small changes of less than ±3 tons per mile.

In WY2009, change in channel silt-and-clay storage was largely affected by the storm of December 11, 2008. Storage increased in the uppermost cross-section group on Waikele Stream (WK1), but large storage reductions of –41 to –134 tons per mile occurred at groups in the middle and lower reaches of the stream (table 8). The lowermost group on Waikele Stream (WK6) could not be measured in WY2009 because the storm flows of December 11, 2008, destroyed all cross-section monuments. Visual evidence of extensive channel erosion suggests that this reach also lost a large amount of channel-bed sediment. In comparison to the large

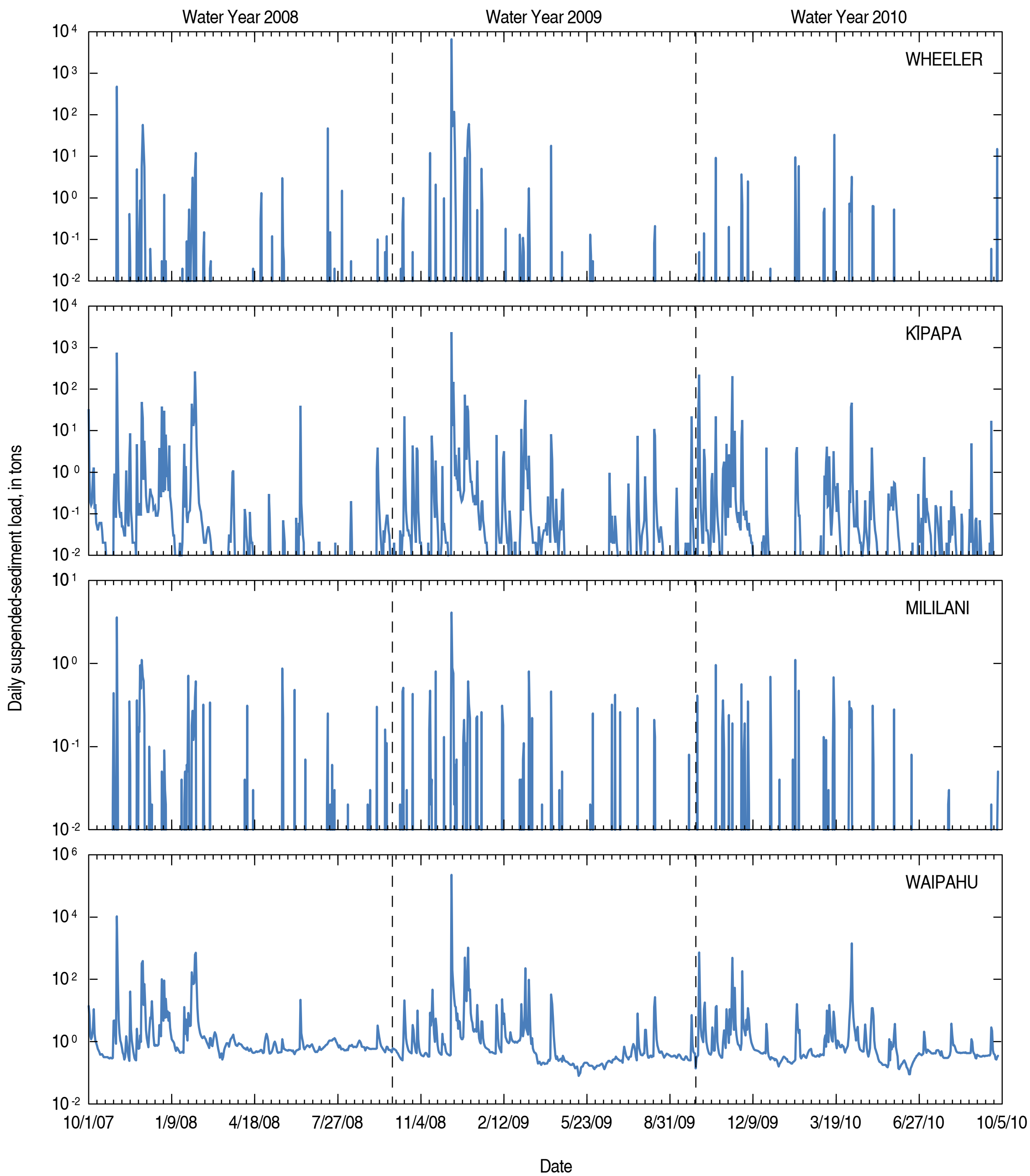


Figure 11. Graphs showing daily mean suspended-sediment load from gages in the Waikele watershed, O‘ahu, Hawai‘i, during the period of this study (water years 2008 to 2010).

Table 9. Suspended-sediment yield for the Waikele watershed and its subbasins, Oʻahu, Hawaiʻi, during period of this study (water years 2008 to 2010).

[Negative change in channel storage indicates erosion. WY, water year, which year begins October 1 of the previous calendar year and ends September 30; tons/yr, tons per year; tons/yr/mi^2, tons per year per square mile]

Water year	Yield (tons/yr)	Change in channel storage (tons/yr)	Yield from hillslopes (tons/yr)	Percentage of basin yield from		Normalized hillslope yield (tons/yr/mi^2)
				Channels	Hillslopes	
Wheeler subbasin						
2008	650	-80	570	12	88	85
2009	7,070	357	7,430	0	100	1,110
2010	88	-34	54	39	61	8.0
Study period	2,600	81	2,680	0	100	399
Kīpapa subbasin						
2008	1,460	-11	1,450	1	99	339
2009	2,910	54	2,970	0	100	694
2010	680	-139	540	20	80	126
Study period	1,690	-32	1,650	2	98	386
Mililani subbasin						
2008	16	assumed negligible	16	assumed negligible	100	29
2009	16	assumed negligible	16	assumed negligible	100	29
2010	9.4	assumed negligible	9.4	assumed negligible	100	17
Study period	14	assumed negligible	14	assumed negligible	100	25
Waipahu Exclusive subbasin						
2008	11,800	80	11,900	0	100	354
2009	220,000	-1,510	218,000	1	99	6,520
2010	2,710	-594	2,120	22	78	63
Study period	78,200	-675	77,500	1	99	2,310
Entire Waikele watershed (represented by Waipahu drainage basin)						
2008	14,000	-10	13,900	0	100	308
2009	230,000	-1,100	229,000	0	100	5,070
2010	3,490	-768	2,720	22	78	60
Study period	82,500	-626	81,900	1	99	1,810

changes in silt-and-clay storage in Waikele Stream channels, changes in Kīpapa Stream (KP1 and KP2) were small. This is consistent with the smaller effect the storm of December 11, 2008, had on flow in Kīpapa Stream.

In WY2010, silt-and-clay storage was reduced in the uppermost groups (KP1, WK1, and WK2), whereas storage increased in the lowermost groups (WK3, WK4, WK5, WK6, and KP2) (table 8). Overall, changes in channel silt-and-clay storage in WY2008 and WY2010 were much less than in WY2009.

Table 9 shows the suspended-sediment yield for the Waikele watershed and its subbasins during the study period. An average change of –626 tons/yr for channel beds in the Waipahu drainage basin indicates net erosion of sediment from the channels in the Waikele watershed during the study period. Annual values for change in channel storage in the Waipahu drainage basin were all negative, indicating channel-bed erosion in the watershed in every year of the study. Change in channel storage was greatest in WY2009 (–1,100 tons/yr), least in WY2008 (–10 tons/yr), and intermediate in WY2010 (–768 tons/yr).

For the period of study, average change in channel storage (table 9) was negative in the Kīpapa and Waipahu Exclusive subbasins and positive in the Wheeler subbasin (channel storage in the Mililani subbasin was assumed negligible). However, the change in channel storage varied substantially between water years. In the Wheeler and Kīpapa subbasins in the uppermost part of the watershed, channel deposition occurred in WY2009 whereas channel erosion occurred in WY2008 and WY2010. In the Waipahu Exclusive subbasin, deposition occurred in WY2008, a large amount of erosion occurred in WY2009, and a smaller amount of erosion occurred in WY2010.

Channel and Hillslope Suspended-Sediment Yield

For the Waikele watershed as a whole, the study-period average suspended-sediment yield from hillslopes was 81,900 tons/yr (table 9). The hillslope suspended-sediment yield was 13,900 tons/yr in WY2008, increased to 229,000 tons/yr in

WY2009, and declined to 2,720 tons/yr in WY2010. A similar pattern is evident in the hillslope suspended-sediment yields for all subbasins except Mililani—suspended-sediment yield was highest in WY2009, which included the storm of December 11, 2008, lowest in WY2010, and intermediate in WY2008.

The normalized suspended-sediment yield from hillslopes in the Waikele watershed as a whole for the study period was 1,810 tons/yr/mi^2 (table 9). The Waikele Exclusive subbasin had by far the largest suspended-sediment yield per square mile of all the subbasins in this study. The average hillslope normalized suspended-sediment yield from this subbasin during the study period (2,310 tons/yr/mi^2) was more than five times larger than that of any other subbasin. In contrast, the hillslope suspended-sediment yield from the Mililani subbasin (25 tons/yr/mi^2) was more than an order of magnitude smaller than the next lowest value (from the Kīpapa subbasin) and about two orders of magnitude lower than the value from the Waipahu Exclusive subbasin. The Wheeler and Kīpapa subbasins had similar hillslope suspended-sediment yields of about 400 tons/yr/mi^2. The wide variability in suspended-sediment yields reflects the activities, land cover, soils, and climate within the subbasins, as well as differences in how the storm of December 11, 2008, affected different parts of the watershed.

Although bank erosion was not assessed in this study, field evidence indicated that bank erosion was not significant except in WY2009. In WY2008 and WY2010, no cross-section monuments were lost and bank vegetation remained intact or in some cases increased, indicating that bank erosion was not substantial. Bank erosion was substantial in WY2009 because of the storm of December 11, 2008. This bank erosion was incorporated into the estimate of change in channel storage for WY2009, but the relative proportion of suspended sediment from channel sources was still only about 1 percent or less (table 9, column 5). These data indicate that although the storm of December 11, 2008, caused substantial bank erosion, it also caused a proportional increase in hillslope suspended-sediment yield.

Discussion

The suspended-sediment yields in this study reflect the particular conditions of the 3-year study period, which may differ from long-term conditions. The Waipahu and Kīpapa gages each had several decades of data collected prior to this study. These data provide an opportunity to compare the flow conditions during the 3-year period of this study with long-term flow conditions.

The general patterns of daily mean streamflow at both the Kīpapa and Waipahu gages during the period of this study were similar to the patterns during previous monitoring periods (fig. 12), but flows during the period of this study were lower than the average flows for the previous periods (table 10). As discussed above, the storm of December 11, 2008, did not affect all parts of the watershed equally, thus although the daily mean streamflow during the storm at both gages was the highest for the study period, only at the Waipahu gage did it also exceed the previous highest daily mean streamflow.

Table 10. Summary of streamflow and suspended-sediment data collected prior to the period of this study from gages in the Waikele watershed, Oʻahu, Hawaiʻi.

[WY, water year, which year begins October 1 of the previous calendar year and ends September 30; ft^3/s, cubic feet per second; ft^3/s/mi^2, cubic feet per second per square mile; tons/yr, tons per year; tons/yr/mi^2, tons per year per square mile]

Kīpapa gage streamflow		
Statistic	**WY1957–WY2004**	**This study**
Highest daily mean	852 ft^3/s	372 ft^3/s
Lowest daily mean	0.00 ft^3/s	0.00 ft^3/s
Average	10 ft^3/s	7.6 ft^3/s
Average runoff	2.5 ft^3/s/mi^2	1.8 ft^3/s/mi^2
Kīpapa gage sediment		
Statistic	**WY1973–WY1982**	**This study**
Highest daily load	7,870 tons	2,350 tons
Lowest daily load	0.00 tons	0.00 tons
Average annual load	5,060 tons/yr	1,690 tons/yr
Normalized average basin yield	1,180 tons/yr/mi^2	395 tons/yr/mi^2
Waipahu gage streamflow		
Statistic	**WY1951–WY2007**	**This study**
Highest daily mean	2,590 ft^3/s	4,270 ft^3/s
Lowest daily mean	0.61 ft^3/s	9.4 ft^3/s
Average	40 ft^3/s	33 ft^3/s
Average runoff	0.88 ft^3/s/mi^2	0.73 ft^3/s/mi^2
Waipahu gage sediment		
Statistic	**WY1972–WY1993**	**This study**
Highest daily load	32,900 tons	227,000 tons
Lowest daily load	0.01 tons	0.09 tons
Average load	23,600 tons/yr	82,500 tons/yr
Normalized average basin yield	522 tons/yr/mi^2	1,830 tons/yr/mi^2

Average suspended-sediment load at the Kīpapa gage during the study period was 1,690 tons/yr, which is only about 33 percent of the average load during the earlier period (5,060 tons/yr for WY1973–1982, table 10) and 40 percent of the average load for the entire 13 years of available suspended-sediment record for the Kīpapa gage (4,250 tons/yr). In contrast, the average suspended-sediment load at the Waipahu gage during the period of this study (82,500 tons/yr) was 3.5 times higher than the average load during the earlier period (23,600 tons/yr; table 10). The study-period average is much higher than the previous-period average at the Waipahu gage primarily because of the storm of December 11, 2008, which accounted for more than 90 percent of the suspended-sediment load measured at the gage during the study period (table 5). The average load for the entire 24 years of available suspended-sediment record for the Waipahu gage is 30,900 tons/yr; the study-period average is 2.7 times higher than this value.

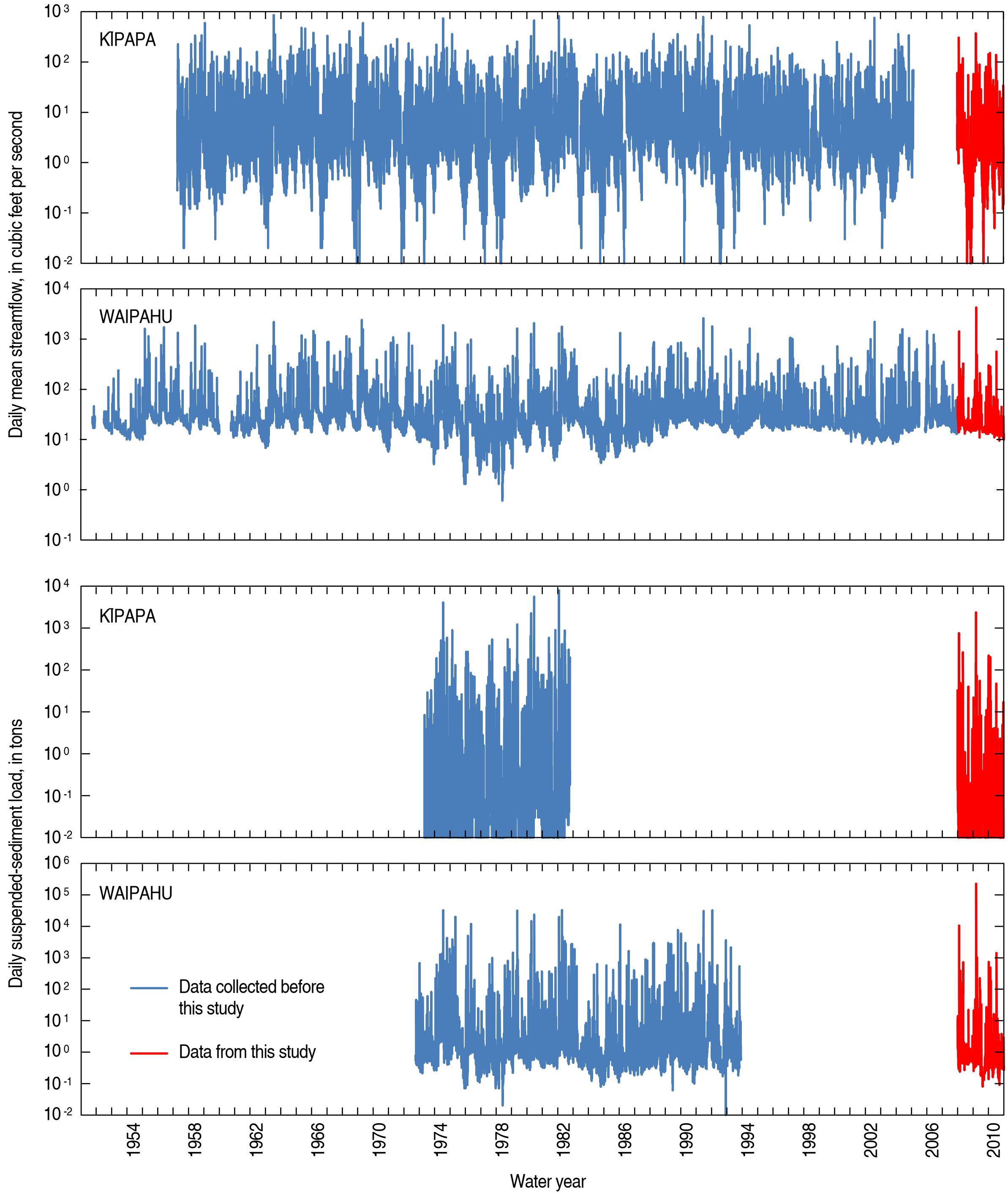


Figure 12. Graphs showing daily mean streamflow and suspended-sediment load for the entire periods of record for the Kīpapa and Waipahu gages, Waikele watershed, Oʻahu, Hawaiʻi.

Although the streamflows and suspended-sediment loads of the study period include the extremes of the December 11, 2008, storm, they are consistent with data from throughout the gage's period of record in showing that a vast majority of suspended-sediment transport occurs during a few large storms. If all 24 years of suspended-sediment data from the Waipahu gage are considered, daily mean streamflows of 200 ft^3/s or higher accounted for more than 90 percent of the total suspended-sediment load, yet occurred less than 2 percent of the time. These results are consistent with those of previous erosion and sediment-transport studies on Oʻahu (for example, Doty, 1981; El Swaify 2000, 2002).

Hillslopes and Channels as Sources of Suspended Sediment

Only a small percentage of the suspended-sediment yield from the Waikele watershed came from channels during this study. Study-period averages for all subbasins indicate that 98 to 100 percent came from hillslopes (table 9). The relative proportion from hillslopes varied substantially by water year, however. Excluding the Mililani subbasin, the proportion of suspended sediment from hillslopes in all subbasins was smallest in WY2010 (61 to 80 percent), largest in WY2009 (99 to 100 percent), and intermediate in WY2008 (88 to 100 percent).

The highest relative proportion of suspended-sediment from channel sources was in WY2010, when 20 to 39 percent of the subbasin suspended-sediment yield came from channel erosion (table 9). WY2010 also had the lowest suspended-sediment yield of the three water years of this study. Streamflow in WY2010 was also low relative to other water years in this study—WY2010 had the lowest mean annual runoff, lowest maximum daily mean streamflow (an indication that storm flows were smaller), and fewest storm-flow peaks of the three water years in this study (table 3, fig. 9). If WY2010 is assumed to be representative of a typical dry year, then the data imply that the proportion of watershed suspended sediment yield contributed by channels is greater during dry years than during wet years, and that during wet years, storms have a greater impact on hillslopes than on channel storage. This hypothesis does not, however, explain why WY2008 had a smaller proportional channel yield than WY2009, even though WY2008 was drier than WY2009. A more likely hypothesis is that the WY2010 results reflect a watershed that was still adjusting to the effects of the December 11, 2008, storm. This hypothesis implies that hillslope sediment supply may have been depleted during the storm, that the storm may have increased availability of channel sediment (for example, by stripping of vegetation growing in the channel or depositing sediment in the channel thereby making more sediment available for subsequent movement), or both. The effect of the storm on sediment sources in the Waikele watershed may have continued beyond the end of the study period.

Suspended-Sediment Yield and Land Use

Land-cover categories from analysis of remote-sensing data by the National Oceanic and Atmospheric Administration (NOAA) (National Oceanic and Atmospheric Administration, 2000) were used to interpret the land uses present in the Waikele watershed (fig. 5). Merging the NOAA land-cover information with data collected in this study facilitated analysis of the relation between suspended-sediment yield and land use. For the purposes of this analysis, the "high-intensity developed" and "low-intensity developed" land-cover categories in the NOAA dataset were interpreted as "urban" land use, and the "evergreen forest" and "scrub/shrub" land-cover categories were interpreted as "forest" land use. The "cultivated land" land-cover category was interpreted as "agricultural" land use. The "grassland" land-cover category was also interpreted as "agricultural" because most of the grasslands in the Waikele watershed are former agricultural lands. About 2 percent of the watershed area is classified as "bare rock" in the NOAA dataset; this small amount was added to the agricultural land-use category in this analysis.

Forest—The Kīpapa subbasin encompasses an area that is entirely covered by forest land use (figs. 3*A* and 5). This subbasin had a normalized hillslope suspended-sediment yield of 386 $tons/yr/mi^2$ during the study period (table 9). This value is much lower than that of the watershed as a whole (1,810 $tons/yr/mi^2$). Part of the difference may be due to the smaller impact the storm of December 11, 2008, had on the Kīpapa subbasin compared to the rest of the watershed. The study period value for the Kīpapa subbasin is, however, within the range of values reported for other forested valleys in wet climates in Hawaiʻi, such as Hanalei, Kauaʻi (275 $tons/yr/mi^2$) (Calhoun and Fletcher, 1999) and valleys on the windward side of the Koʻolau Mountains (710 to 1,400 $tons/yr/mi^2$) (Jones and others, 1971). The suspended-sediment yields from the Kīpapa subbasin may be higher than the average suspended-sediment yield from forests in the Waikele watershed as a whole because some forests in the watershed, such as those in the Waiʻanae Mountains, are in drier areas. Suspended-sediment-yield data from undeveloped forest areas in the Waiʻanae Mountains are not available, but Doty and others (1981) reported a suspended-sediment yield of 153 $tons/yr/mi^2$ from Moanalua Valley, which is in a part of the Koʻolau Mountains that is drier than the Kīpapa subbasin. Their analysis was for a period when runoff averaged 0.32 $ft^3/s/mi^2$, which is between the study-period average runoff values for the Wheeler and Kīpapa subbasins in this study (table 3). This indicates that the suspended-sediment yield from forested areas in drier parts of the Waikele watershed may be as much as 60 percent lower than indicated by the study-period normalized hillslope suspended-sediment yield from the Kīpapa subbasin.

Urban—The Mililani subbasin encompasses an area that is covered entirely by urban land use (fig. 5); this subbasin had a normalized hillslope suspended-sediment

Table 11. Estimated suspended-sediment yields from land uses in the Waipahu Exclusive subbasin, Waikele watershed, O‘ahu, Hawai‘i, during the period of this study (water years 2008 to 2010).

[tons/yr/mi^2, tons per year per square mile; mi^2, square mile; tons/yr, tons per year]

Land use	Estimated normalized yield for study period (tons/yr/mi^2)	Waipahu Exclusive subbasin		
		Area (mi^2)	Yield (tons/yr)	Percent of total yield
Urban	12–50	5.19	62–260	0.1–0.4
Forest	193–772	16.87	3,260–13,000	4.2–16.8
Agriculture	5,580–6,440	11.51	64,200–74,200	82.9–95.7

yield of 25 tons/yr/mi^2 (table 9), which is more than an order of magnitude less than the forested Kīpapa subbasin and nearly two orders of magnitude less than the watershed as a whole. Part of the disparity may be attributed to differences in rainfall—the Mililani subbasin is in a relatively dry part of the watershed. However, suspended-sediment yield from the Mililani subbasin was still relatively small during the storm of December 11, 2008 (tables 3 and 4); whereas most suspended-sediment transport occurs during storms, it is likely that the differences in suspended-sediment yields were primarily the result of factors other than rainfall, such as urbanization. The pavement, buildings, storm drains, and maintained grassy areas in the mature residential development encompassed by the Mililani subbasin probably reduced erosion by water during the study period. The suspended-sediment yield from the Mililani subbasin may be lower than the average suspended-sediment yield from urban areas in the Waikele watershed as a whole because some urban areas are wetter than the Mililani subbasin (figs. 2 and 5). Even so, the data indicate that areas in the watershed with urban land use yield much less suspended sediment than areas with other land uses.

Agriculture —The Waipahu Exclusive subbasin encompasses an area that has a mixture of land uses (figs. 3*B* and 5). Of the 33.58 square miles encompassed by the basin, 16.87 mi^2 (50 percent) is forest, 5.19 mi^2 (16 percent) is urban, and 11.51 mi^2 (34 percent) is agricultural land use. An estimate of the suspended-sediment yield from agricultural land use in the subbasin can be computed by assuming that areas with urban land use had the same normalized hillslope suspended-sediment yield as the Mililani subbasin and that areas with forest land use had the same normalized hillslope suspended-sediment yield as the Kīpapa subbasin (table 9). Multiplying the normalized suspended-sediment yields by the respective areas indicates that of the 77,500 tons/yr of suspended sediment yielded from hillslopes in the Waipahu Exclusive subbasin during the study period, 130 tons/yr came from areas with urban land use and 6,510 tons/yr came from areas with forest land use; the remaining 70,900 tons/yr or 6,160 tons/yr/mi^2 is an estimate of the suspended-sediment yield from areas with agricultural land use.

Accuracy of this estimate hinges on the assumption that the yields from the Kīpapa and Mililani subbasins are transferable to other areas of forest and urban land use in the Waipahu Exclusive subbasin. As discussed above, the suspended-sediment yield from the Kīpapa subbasin is probably higher than the average suspended-sediment yield for forested areas in the watershed, whereas the suspended-sediment yield from the Mililani subbasin is probably lower than the average suspended-sediment yield for urban areas in the watershed. To assess the uncertainty related to the assumed suspended-sediment yields for forest and urban areas, the agricultural suspended-sediment yield estimate was recomputed using a range of values from 0.5 to 2.0 times the values indicated by the Kīpapa and Mililani subbasins. The results indicate that suspended-sediment yield from agricultural land use was between 5,580 and 6,440 tons/yr/mi^2 during the study period (table 11). Of the three land uses considered, agriculture had by far the highest normalized suspended-sediment yield during this study—about an order of magnitude higher than forests and two orders of magnitude higher than urban areas. Inasmuch as this estimate is based on a study period in which average suspended-sediment yield from the watershed was about 2.7 times greater than the long-term mean, the long-term suspended-sediment yield from agricultural land may be closer to 2,070 to 2,390 tons/yr/mi^2.

In comparison, El Swaify (2000) reported a yield of 2,036 tons/yr/mi^2 for pineapple fields in Kunia, which lie in the Waikele watershed (his grain-size analysis indicated that 96 percent of the Kunia soil was less than 0.050 mm; therefore, his results are generally comparable to the suspended-sediment results in this study). The long-term estimate of suspended-sediment yield from the Waipahu Exclusive subbasin in this study is higher than El Swaify's value, but within the range of yields reported from other agricultural areas (for example, Dunne and Leopold, 1978, El Swaify and others, 1982; Clune and others, 2010). A change from sugarcane and pineapple agriculture to forms of agriculture that require more periods of soil disturbance could increase soil loss (El Swaify, 2002), but the specific practices of current agriculture in the watershed were not assessed in this study.

Study Limitations

The approach of this study was appropriate for the scope and met the objectives of identifying sources of suspended sediment in the Waikele watershed. Most of the techniques used were successfully used in previous sediment-transport studies in Hawaiʻi (for example, Hill and others, 1998). Even so, a retrospective of the limitations of this study can serve to identify possible method improvements and potential avenues for research to advance understanding fluvial sediment transport in Hawaiʻi.

This study assumed that the non-conservative nature of sand in the suspended load had a negligible effect on the assessment of sediment yields. This assumption was based on grain-size analyses conducted on selected suspended-sediment samples collected by the gages; these analyses indicated that sand constitutes only a small fraction of the suspended-sediment load in the Waikele watershed. Inasmuch as the proportion of sand in the suspended load can vary across the width of the stream channel and with flow rate, the basis for the assumption could be improved with grain-size analyses of samples from a wider range of flows and from across the entire channel width.

Particle attrition also contributes to the non-conservative nature of the suspended load. Some alluvial clasts, particularly sand and small pebbles, are highly weathered and can disintegrate quickly during stream transport. As a result, some particles that are transported as bedload in upper reaches of the watershed can disaggregate to particles small enough to become part of the suspended load in the lower watershed. Hill and others (1998) conducted particle-attrition experiments on bed sediments from North Halawa Stream, which are mineralogically and texturally similar to bed sediments in the Waikele watershed, and found that 36±4 percent of the mass of a sample of sand-and-coarser bed material was converted to sediment 0.063 mm and finer (silt or clay) after 5 miles of simulated transport in a tumbler. Although pebble counts and grain-size analysis indicate that only a small fraction of channel sediment in the Waikele watershed is finer than sand, results of this study may underestimate the contribution from channel storage because particle attrition was not considered.

Using a finite number of gages and cross sections to characterize sediment yields throughout the watershed required spatial extrapolation. Additional gages and cross sections can increase the accuracy of assessing sediment yields from the various parts and land uses in the watershed. Drawing conclusions about long-term sediment transport from the data collected in the 3-year monitoring period also required extrapolation over time. As discussed, the extreme storm of December 11, 2008, dominated sediment transport in the study period and may have affected sediment yields in subsequent years. Long-term streamflow/sediment monitoring can help place the extreme results from this study period in the context of long-term sediment yields in the watershed.

This study investigated sources of sediment from the subbasins and land uses in the Waikele watershed; the study did not address the mechanisms of erosion that cause the sediment yields to differ from one location to the next. The suspended-sediment and streamflow data from this study can, however, be used in conjunction with data on soil properties, land cover, slope, and rainfall to identify the predominant erosion mechanisms in various areas of the watershed, study the details of the process by which these mechanisms generate sediment, or assess implications for the rates of soil loss, landscape lowering, or sediment delivery to receiving waters.

This study monitored suspended-sediment concentrations (SSC) in the Waikele watershed. Other parameters commonly used in regulating sediment impacts on natural waters include total suspended solids (TSS) and turbidity (U.S. Environmental Protection Agency, 1999). For TSS, a split of the sample is analyzed, whereas for SSC, the whole sample is analyzed. Due to problems inherent in the splitting procedure, TSS tends to underestimate sediment concentration when sand constitutes a quarter or more of the suspended load (Gray and others, 2000). In this study, however, only 13 percent of the suspended-sediment samples analyzed for grain size had more than 25 percent sand. The correlation between turbidity and sediment concentration varies from one location to the next (U.S. Environmental Protection Agency, 1999). For natural water bodies, such as those in the Waikele watershed, the suspended-sediment-concentration method produces more reliable results (Gray and others, 2000).

Summary and Conclusions

Average streamflow from the Waikele watershed during the study period was lower than the long-term average. Interannual variations in streamflow among the 3 years of this study correspond with variations in the frequency and magnitude of storm-flow peaks from one year to the next. Flows during the December 11, 2008, storm (in WY2009) accounted for a substantial part of the study-period total streamflow from the watershed.

Suspended-sediment yield from the Waikele watershed averaged 82,500 tons/yr during the study period, with daily yields ranging widely from 0.08 tons to 227,000 tons. More than 90 percent of the yield during the study period was discharged during the December 11, 2008, storm. The average yield during the study period was 2.7 times higher than the long-term average. The study-period results are consistent with long-term records in that the vast majority of suspended-sediment transport occurs during a few large storms. If all 24 years of suspended-sediment data from the Waipahu gage are considered, daily mean streamflows of 200 ft^3/s or higher account for more than 90 percent of the total load, yet occurred less than 2 percent of the time.

All but a small percentage of the suspended-sediment yield from the Waikele watershed came from hillslopes during this study. Only a small fraction of the volume of bed sediments in the Waikele watershed are fine enough to be transported as suspended load. Channel sediments throughout most of the Waikele watershed consist mostly of sediment particles ranging from boulders to sand; the average proportion of the bed-sediment volume consisting of silt and clay was only 2.4 percent. Some larger clasts, however, are composed of highly weathered rock that can disintegrate into silt and clay during stream transport and contribute to the suspended loads downstream. Results of this study may underestimate the contribution from channel storage because particle attrition was not considered.

The average suspended-sediment yield from hillslopes in the watershed during the study period was 81,900 tons/yr (99 percent of total), compared to only 626 tons/yr (1 percent of total) from channel beds. The highest relative yield from channel sources (22 percent) was in WY2010. It is likely, however, that the WY2010 results partly reflect a watershed that was still adjusting to the effects of the December 11, 2008, storm. The storm may have depleted hillslope sediment supply, increased availability of channel sediment, or both. The effect of the storm may have continued beyond WY2010.

The forested Kīpapa subbasin had an average normalized hillslope suspended-sediment yield of 386 tons/yr/mi^2 during the study period. This value is within the range reported in studies of other forested valleys in wet climates in Hawai‘i, but may be higher than forested areas in drier parts of the watershed. Yields from forests in drier parts of the Waikele watershed may be as much as 60 percent lower than indicated by data from the Kīpapa subbasin.

The study-period normalized suspended-sediment yield from the urbanized Mililani subbasin (25 tons/yr/mi^2) was much smaller than any other subbasin, which suggests that yield from areas with urban land use is much less than yields from areas with other land uses. The Mililani subbasin is in a relatively dry part of the watershed, however. Yields from urbanized areas in wetter parts of the watershed may be higher.

The Waipahu Exclusive subbasin, which has a mix of land uses including forest (50 percent), urban (16 percent), and agriculture (34 percent), had a normalized suspended-sediment yield (2,310 tons/yr/mi^2) that was nearly six times larger than that of any other subbasin. The average suspended-sediment yield from agricultural land use in the watershed is estimated to range between 5,590 and 6,440 tons/yr/mi^2 during the study period; the long-term average is estimated to be 2,070 to 2,390 tons/yr/mi^2. Of the three land uses considered, agriculture had by far the highest normalized suspended-sediment yield during this study—about an order of magnitude higher than forests and two orders of magnitude higher than urban areas. This estimate is higher than previous studies on pineapple and sugarcane fields in Hawai‘i but within the range of reported agricultural yields from other tropical areas.

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Glossary

Annual exceedance probability—In streamflow statistics, probability that a specified flow will be equaled or exceeded in a given year.

Base flow—Streamflow that persists during dry periods; this flow is commonly from groundwater discharge.

Box coefficient—Ratio of the average suspended-sediment concentration across the width of streamflow to the concentration at a point, such as the location of an automatic sampler intake orifice.

Bulk density—For sediment, dry mass per volume, including clasts and pore spaces.

Channel-bed sediment storage—Amount of sediment stored in a channel bed; does not include sediment stored in other parts in and near the channel bed such as banks and flood plains.

Clast—Sediment particle, such as a boulder, cobble, pebble, sand grain, or silt or clay particle.

Drainage area—Area contributing runoff to a specified location on a stream, such as the location of a streamgage.

Hillslope—Area between stream channels; specifically in this report, all areas outside stream channels shown on the U.S. Geological Survey 1:24,000-scale topographic maps.

Hydrograph—Graph of stream stage or flow versus time.

Load—Quantity of sediment transported by a stream past a specified location, such as the site of a streamflow/sediment gage.

National Water Information System (NWIS)—Water database of the U.S. Geological Survey, accessible through the Internet at http://waterdata.usgs.gov/nwis.

Normalized yield—Yield divided by its source area.

Point concentration—In sediment studies, concentration of sediment at a point in the stream, such as the location of the intake orifice of a sampler or a streamflow/sediment gage.

Rating curve—Curve on a graph of the relation between stage and streamflow.

Recurrence interval—Reciprocal of the annual exceedance probability.

Runoff—Streamflow divided by the area of the drainage basin.

Stage—In streamgaging, the level of the water surface in a stream.

Stream order—Numerical value assigned to a reach of stream on the basis of its position in a stream network; lowest numbers are assigned to uppermost reaches.

Suspended sediment—Sediment suspended in water, such as in the water of a stream.

Suspended-sediment budget—Mass balance of the sources and sinks of suspended sediment in a watershed or basin.

Yield—Quantity of sediment shed from a specified source, such as a drainage basin or particular land use.

Water year—Twelve-month period from October 1 to September 30; for example, the 2008 water year spans the period from October 1, 2007, to September 30, 2008.

Wentworth scale—Classification of sediment particle size: boulder, greater than 256 millimeters (mm); cobble, 64 to 256 mm; pebble, 2 to 64 mm; sand, 0.063 to 2 mm; silt and clay, less than 0.063 mm.

Wolman pebble count—Field method for quantifying grain-size distribution in streambed sediment.

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