EROSION AND SEDIMENT LOADS FROM TWO HAWAIIAN WATERSHEDS

Jonathan Stock, USGS Earth Surface Processes Team, Menlo Park, CA, jstock@usgs.gov,
Gordon Tribble, USGS Pacific Islands Water Science Center, Honolulu, HI,
gtribble@usgs.gov

INTRODUCTION

Fine sediment eroded from the subtropical islands of Hawaii decreases coastal water quality and likely degrades coral reef ecosystems. Coastal ecosystems are vital parts of Hawaii's tourist and resource extraction economies, so we are studying the source, rate and future loading of sediment to the nearshore. As part of the USGS Ridge to Reef program, streamflow and suspended sediment load have been monitored in two watersheds in Hawaii (Fig. 1) where coastal resource degradation is thought to be particularly severe. The Hanalei River drains a wet, steep-walled, heavily forested basin on the north shore of Kauai. The Kawela basin drains arid, shrubby grassland on the south shore of Molokai. Although their vegetation and mean annual rainfall totals contrast, sediment discharge from both watersheds is locally perceived to be impacting their nearshore ecosystems. We hypothesize that the geomorphic processes producing fine sediment vary between these catchments because of differences in geology, rainfall distribution and total, and vegetation. We use suspended sediment and discharge records for gages at these two watersheds to explore this hypothesis. These data represent two of the longest records of suspended sediment in the Hawaiian Islands. Because of the strong connection with vegetation, and the need to understand sediment dynamics in the reef environment, our work is coordinated with biological studies within the watersheds and reefs and with marine studies of circulation and sedimentation patterns in nearshore waters.

STUDY AREAS

The Kawela watershed (5.3 mi^2) drains the dry, southern side of Molokai (Fig. 1). Average annual rainfall ranges from about 120 inches near the summit to about 20 inches at the coast (Giambelluca et al, 1986), The upper 1/3rd of the watershed lies above the forest edge and receives a steady input of fog drip and light rain from tradewind dominated rainfall. Rainfall input below the forest line is dominated by one to several low pressure cyclonal storms per year (average of 34 rainy days per year). Vegetation below the forest line consists of patchy shrubs, grass, and dense acacia near the shoreline (e.g., Fig. 2A).

Interbedded alkalic and tholeiitic basalt flows form a leaky bedrock basement at Kawela. Although flow in the upper forested area is perennial, transmission losses along the stream are large enough that flow at the coast near the stream gage is intermittent. Kawela valley walls expose numerous alkalic vents with associated phreatomagmatic products, including deposits of silt-sized tephra (Fig. 2C, D), a likely source for fine sediment in runoff. The upper third of the watershed remains a largely intact cloud forest under the management of The Nature Conservancy. The lower 2/3rds of the watershed is heavily grazed by feral goats and pigs. Overland flow is widespread here where removal of vegetation has exposed low permeability silts. Studies in progress indicate that the majority of the fine sediment transported by the stream comes from overgrazed, silt deposits, subjected to bursts of erosion during high intensity cyclonal storms (Stock et al, 2009). A broad (about ½ mile) reef flat extends from the shoreline, and live coral covers up to 80% of the submarine slope from the reef crest to a depth of about 80 feet. The wave regime is mild because the island of Lanai blocks large southerly swells that would otherwise impact the reef (see Field and others, 2008).

The Hanalei watershed (18.7 mi^2) is on the wet, windward side of Kauai. Average annual rainfall ranges from over 430 inches near to summit to 80 inches at the coast (Giambelluca et al, 1986). The watershed is cut into thin-bedded tholeiitic flows, which are locally highly weathered. Fine-grained tephra is not known to be exposed within the basin. Landslides are common in the wake of large cyclonal storms (e.g., Fig. 2F, G). The river valley has a floodplain (blue in Fig. 1), and there are substantial terrace deposits of sand and silt here, unlike in Kawela (Fig. 2B). The watershed is heavily vegetated (Fig. 2E) and harbors large numbers of feral pigs. Hanalei Bay is dominated by a mix of unconsolidated marine and terrestrial sediment to depths of 50 feet or greater. The reefs that line the perimeter of the bay support limited but healthy coral communities (Friedlander et al., 2005; Draut et al., 2009; Storlazzi et al., 2009). The bay is seasonally subject to frequent NW swells in excess of 20 feet.

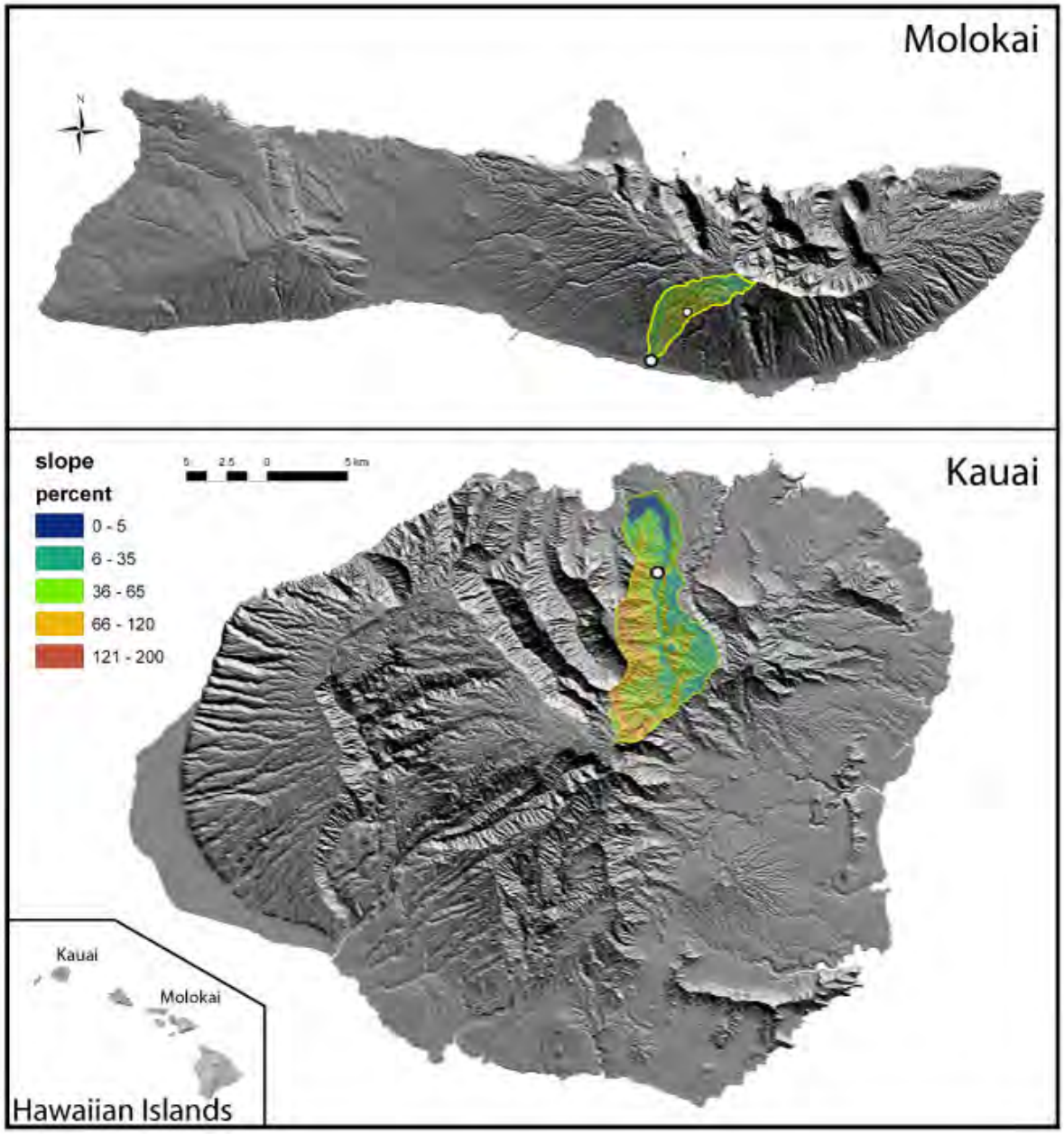

Figure 1. Shaded relief maps of the Kawela basin on Molokai (top) and the Hanalei River basin on Kauai (bottom) from USGS 10-m DEMs. Larger circles indicate USGS stream gages at Kawela (Station 16415600) and Hanalei (Station 16103000). Smaller circle indicates the experimental site in Kawela where we are monitoring hillslope runoff and suspended sediment. Slopes are binned to indicate hypothetical areas of fan and floodplain deposition (5 % or less), areas of linear hillslope creep and overland flow (6-35 %), areas of non-linear hillslope creep and overland flow (36-65 %), areas prone to rockfall and landsliding (66-120 %), and areas too steep to retain large quantities of soil (> 121%). The divisions illustrate that large portions of the western Hanalei basin are steep, bedrock areas with minor soil in residence. Approximately 1/3 of the Kawela basin area are steep, rock walls.

The climate in Hawaii has become measurably drier since the early part of the 20th century (Oki, 2004, Chu and Chen, 2005). The degree of aridity during the period of our study (Oct 2004 through Sept 2008) is similar to the overall decade (2000-2009), as measured by the average area of the State that was in drought condition: for the decade as a whole, an average of 53.7% of the state was in drought, whereas for the period of study 55.1% was in a

drought condition (US Drought Monitor, 2009). There is a high degree of interannual variability. In the Kawela watershed, annual rainfall totals from 2003-2008 were 22-72 inches in the forested highlands (median value of 47 inches; Molokai1 RAWS site, 2002-2007), and 3-27 inches at the coast (median value of 15 inches; Feeter residence rain gage, 1996-2007).

SEDIMENT SUPPLY

Vegetation and geology influence the supply and grainsize of sediments exiting each basin. The upper 1/3 of Kawela is densely vegetated, and hillslope sediment supply is from episodic soil creep and perhaps landslides. Field inspections of Kawela Stream in this upper portion indicate a perennial stream with coarse bed material, and few fines. With the exception of two backwater areas where fines have deposited near the basin mouth, banks are comprised of coarser material and bank erosion would not supply significant suspended sediment. The lower 2/3rds of the watershed is sparsely vegetated (Fig. 2). Sediment supply here is dominated by rockfall of coarse particles in 1/3rd of the area (Fig 2B), and rainsplash and overland flow in the remaining 1/3rd (Fig. 2C, D). The tributaries draining the mid-slope Kawela catchment appear to flow only during intense rainfall events. Flow in these channels is ephemeral, and silt and finer sediments can be found under coarser particles in the bed, offering a ready supply of fines even at low flow. Bank exposures of fines occur at two localities where backwater appears to have caused ponding. Overland flow and rainsplash occur where vegetation has been severely reduced, largely as a result of feral animal grazing. Soils in these areas are thin (< 1 foot), except where old tephra deposits have been exhumed (e.g., Fig 2C, D). In these areas, pockets of silt can be many feet deep, and represent large reservoirs of erodible fine particles. Field monitoring studies in progress indicate that these hillslope sites can lower at rates up to ~ 1.6 cm/a in years of 2 or more cyclonal storms with prolonged heavy rainfall. An automated ISCO pump at the channel head below an unvegetated hillslope samples runoff containing suspended sediment. It appears that sediment supply can be depleted during the course of a multi-day storm (Stock et al., 2009), although we do not observe this effect for shorter duration storms.

In contrast, the processes that provide fine sediment to Hanalei Bay are poorly understood. Some of the possibilities include:

1) storm-triggered landslides and debris flows
2) overland flow from areas impacted by feral pigs
3) erosion of fine deposits from streambanks
4) decreased trapping of fine sediment in floodplain
5) entrainment of floodplain deposits.

Reconnaissance in the Hanalei basin indicates that shallow translational landslides do occur within topographic hollows of the steep walls of the basin (Fig. 2G). Some appear to mobilize into debris flows, although we have no evidence that these have reached the mainstem in large numbers over the past decade. Dense vegetation appears to shield hillslope sediments from overland flow erosion except in areas of feral pig activity. Hanalei River valley contains fill terraces of gravel, sand and finer sediments. Unvegetated bank exposures indicate bank erosion (e.g., Fig. 2F), although the extent and rate of bank erosion are unknown. Bank erosion here would produce sediment that could be suspended. There are no compelling data sets on the influence of historic floodplain processes here, although work by Calhoun and Fletcher (1999) indicates that the Late Holocene floodplain aggraded at rates from 0.07-3.06 mm/a.

The observations above lead to a conflicting set of expectations about the evolution of suspended sediment concentration (e.g., Walling and Webb, 1982; Williams, 1989) in both rivers during large rainfall events. Kawela's many unvegetated areas should generate a higher sediment concentration for a given discharge than Hanalei because of readily available sediment sources (e.g., Fig. 2C, D). However, infrequent rainfall and intermittent flow at Kawela may result in a sediment load lower than that of the rainy, perennially flowing Hanalei River.

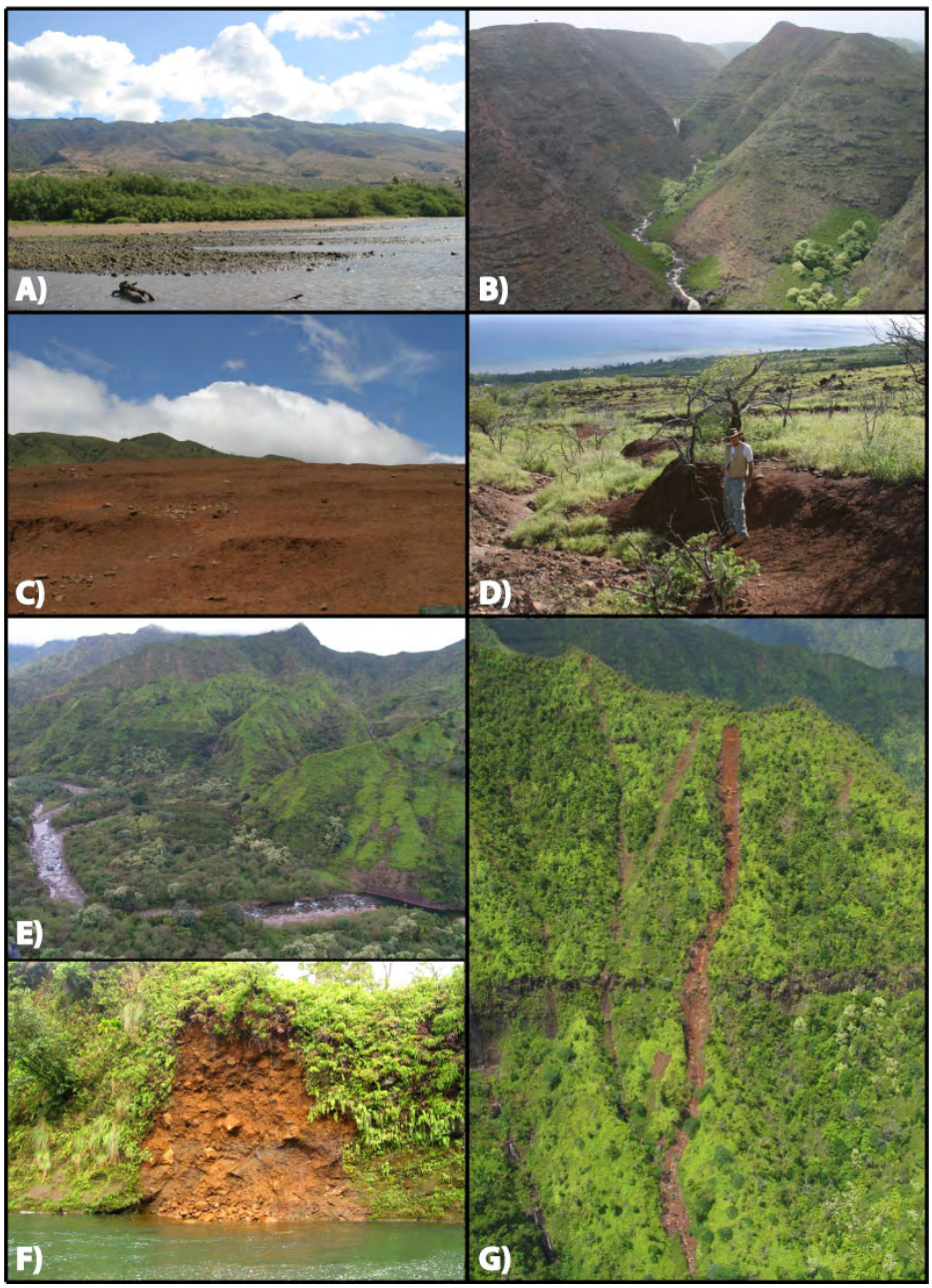

Figure 2. A) View northward to Kawela catchment, illustrating shrub/grassland cover in mid-catchment area. B) View of Kawela Stream during a runoff event. Note rockfall-dominated valley walls, and confined valley floor. C) Contrasting vegetation cover in mid-Kawela catchment. Deposit in foreground has a modal grainsize of silt and likely represents a ~ 1.45 Ma tephra deposit. Studies in progress indicate that rainfall intensities above ~ 10 mm/hour will generate overland flow and erosion of these surfaces. D) Barry Hill provides scale for a 1.5 m deep gully cutting into old tephra deposits in Kawela. E) View of Hanalei River above the stream gage. Wide valley bottom contains legacy deposits of older events. Steep sidewalls to right of photo are dominated by shallow translational landsliding. F) Bank failure in legacy deposits moved fine sediment directly into mainstem Hanalei River (Photo from Jim Jacobi, USGS); G) Shallow translational landslide in a topographic hollow, mobilized into a debris flow. Many of these debris flows appear to deposit before they reach the mainstem (Photo from Jim Jacobi, USGS).

METHODS

We used data from USGS gages in the Kawela (USGS Station Number 16415600) and Hanalei (USGS Station Number 16103000) watersheds. The Kawela gage begin operating in 2001 as a crest-stage gage to record peak annual discharge, and was modified on Oct. 1, 2004 to measure continuous discharge and to collect suspended sediment samples. It is located near the mouth of the watershed (Fig. 1). The Hanalei gage has recorded continuous discharge from 1912 to 1919 and again from 1963 to the present. However, flow upstream of this was gage was diverted into the Hanalei Tunnel until 1993, so low-flow discharges before then are not representative of natural flows from this watershed. On Oct. 1, 2004, the Hanalei gage was modified to collect suspended sediment samples.

Direct measurements of discharge are made periodically by the USGS at all stream-gaging and stream water-quality stations using standard practices (Rantz and others, 1982). Peak flows that could not be measured with current meters were determined using the slope-area method (Dalrymple and Benson, 1968) or other indirect methods (Buchanan and Somers, 1969: Rantz and others, 1982). Continuous-discharge data were computed by USGS using the discharge measurements and water level or stage recorded at each of the stations as described by Rantz and others (1982). Sediment loads were calculated for both basins for the period of study, except there are no sediment data for Hanalei from Oct. 1, 2006 to Sept. 30, 2007. Sample collection, sediment analysis, and load calculations were done using standard USGS methods (Edwards and Glysson, 1999; Davis et al., 2005).

We used automated pump samplers (ISCO) to collect runoff at Kawela and Hanalei. The samplers were programmed to collect samples during storm flows that reached specified thresholds and, in the case of the Hanalei gage, also collect samples at regular intervals (usually every two days) during non-storm periods. We used these samples to determine suspended-sediment concentrations. Sediment discharges for days of rapidly changing flow or concentration were computed by the subdivided-day method (time-discharge weighted average). Methods to calculate sediment loads are described by Porterfield (1972) and Koltun and others (2006).

In the Kawela watershed, silts lying along the dry watercourses will be entrained at the lowest of stages, and higher stages will continue to entrain fines as the gravel layer begins to move, exposing shielded fines. For short duration flows that do not exhaust these small reservoirs, discharge vs. concentration may be approximately log-log linear. Prolonged flow likely results in an elongate clockwise hysteresis curve as bed material supply is depleted (e.g., Klein, 1984; Ahanger et al., 2008; Smith & Dragovich, 2009). For long duration rainfalls exceeding ~ 10 mm/hour (or about ½ inch/hour) we expect to begin to see clockwise hysteresis as loose, weathered silt is depleted from the hillslope reservoirs (Stock et al., 2009). This effect will be most pronounced during very long storms, or for storms that immediately follow a strong storm. We do not expect to observe strong counter-clockwise loops because of the absence of bank sources for fines that could provide large inputs of fine sediment during the falling stage.

In Hanalei, shallow translational slides and associated debris flows likely occur during the peak intensity rainfall of a storm. To the extent that peak rainfall rates generate peak discharges, we expect to see a log-log linear relation with these events. If streambank erosion is a large source of fines in Hanalei, we expect to see counter-clockwise hysteresis because bank erosion will likely occur at peak stages or on the declining limb when saturated banks are susceptible to undermining. This would lead to an increase in fines even as discharge declines.

To detect these potential hysteresis patterns, we extracted all of the events from the suspended sediment record that included at least 5 sequential samples separated by an hour or less. We took these events and divided them into linear segments that rose and fell along the same trend, clockwise segments where sediment concentration declined through time relative to discharge, and counter-clockwise segments where sediment concentration increased through time relative to discharge. We did not include data with less than 5 consecutive samples because it is not clear whether these points represent parts of a hysteresis curve, or linear segments. In the Kawela record, 194 out of 220 samples can be used to reconstruct events. At Hanalei, 159 out of 1,063 records meet the minimum criteria of 5 contiguous samples.

RESULTS

STREAMFLOW AND SUSPENDED SEDIMENT LOAD IN KAWELA AND HANALEI WATERSHEDS

Flow in Kawela Stream gage is intermittent (Fig. 3), occurring only 36.7% of days during the period of our study (Oct. 1, 2004 to Sept. 30, 2008). For those days with measured flow, the median discharge was 3.2 cfs. The peak flow during this period was 1,920 cfs (Nov. 2, 2006); the record (since Oct 1, 2001) peak flow of 3,190 cfs occurred on Nov 27, 2001.

In contrast, flow in the Hanalei River is perennial. For the period of study, the median discharge was 121 cfs (Fig. 3). This is slightly lower than the measured long-term median flow of 129 cfs (since 1993). The peak flow at this gage during the study period was 15,300 cfs; the record peak flow of 44,600 cfs occurred on Nov. 3, 1995.

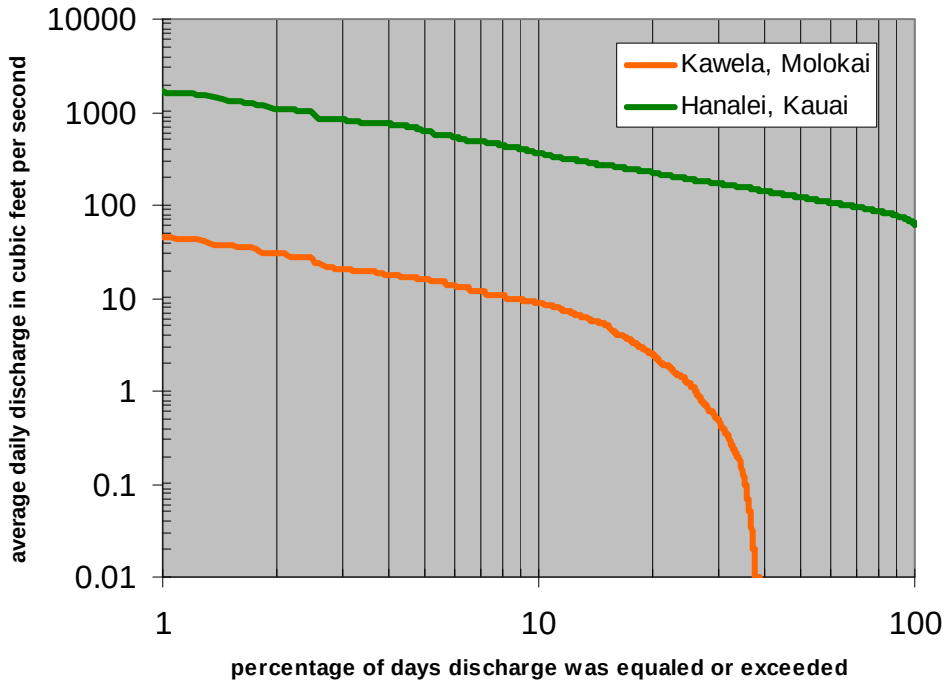

Figure 3. Flow duration curve calculated using daily average discharge from October 1, 2004 to September 30, 2008. Hanalei River is perennial. Kawela stream is intermittent and has measurable flow at its gaging station about 134 days (36.7%) out of the year.

The two watersheds differ dramatically in the amount and timing of suspended sediment load. In Kawela, the average monthly load was 450 tons (Fig. 4, top), and the largest daily load was 4,310 tons. 50% of the load was transported on 0.3% of the days, and 90% of the load was transported on 1.0% of the days. Normalized to the drainage area of the watershed, average annual load was 1,020 tons/mi^2. In Hanalei, the average monthly load was 2,120 tons (Fig. 4, bottom), and the largest daily load was 14,000 tons. 50% of the load was transported on 0.5% of the days, and 90% of the load was transported on 5.1% of the days. Normalized to the drainage area of the watershed, average annual load was 1,361 tons/mi^2. This annual load represents 10% of the estimated Late Holocene sediment in the Hanalei floodplain (Calhoun & Fletcher, 1999), which would take ~ 400 years to form at current supply rates.

Given a saprolite bulk density of 1,200 kg/m^3, the average annual suspended load at Hanalei represents a basin-wide lowering rate of 0.44 mm/a, and that of Kawela a rate of 0.33 mm/a. For soil bulk densities of 950 kg/m^3, Hanalei basin surface lowering is 0.56 mm/a, and that of Kawela basin is 0.42 mm/a. Bedrock densities of 3,000 kg/m^3 result in Hanalei lowering rates of 0.18 mm/a, and Kawela lowering rates of 0.13 mm/a.

SUSPENDED SEDIMENT CONCENTRATION

The two watersheds showed very different relationships between suspended sediment concentration and instantaneous flow (Fig. 5). There is a crude log-log linear trend to the data (Fig. 5), with much scatter about the regression lines. The slope and intercept of the Kawela data are higher than values from the Hanalei data. The Hanalei rating here supersedes the initial ratings curve proposed by Calhoun and Fletcher (1999), which was based on limited data acquired during 1995. Over the period of study, 1,063 suspended sediment samples were collected at the Hanalei gage, and 220 were collected at the Kawela gage. The Hanalei samples had an average suspended sediment concentration of 63 mg/L, with a maximum value of 2,750 mg/l (at an instantaneous flow of 14,100 cfs). The Kawela samples had an average suspended sediment concentration of 3,490 mg/L, with a maximum value of 54,000 mg/l (at an instantaneous flow of 57 cfs). Sand sized particles were noted in some of the Kawela samples, and it appears that at even modest flows in Kawela stream can transport high levels of suspended sediment. The inclusion of bedload is a possibility, but a visual inspection of the sampling orifice line after storms was used as a criterion to discard samples from events contaminated by bedload.

Figure 6 highlights log-log linear (bold black fitted lines), clockwise (bold red, yellow, green and blue lines), and counter-clockwise (bold orange) parts of the suspended sediment concentration data from Kawela and Hanalei. The slope of the log-log linear data at Kawela is nearly double that at Hanalei, indicating a much higher sediment increase in concentration per increase in unit discharge. Crudely, at similar discharges, the sediment concentrations at Kawela are from 1 to several orders of magnitude higher than those observed at Hanalei River. Although the intercepts are similar in magnitude, there is a rapid increase in observed sediment concentrations at low flow (10-20 cfs) in Kawela. This vertical data cloud indicates a supply of fines even at low flows.

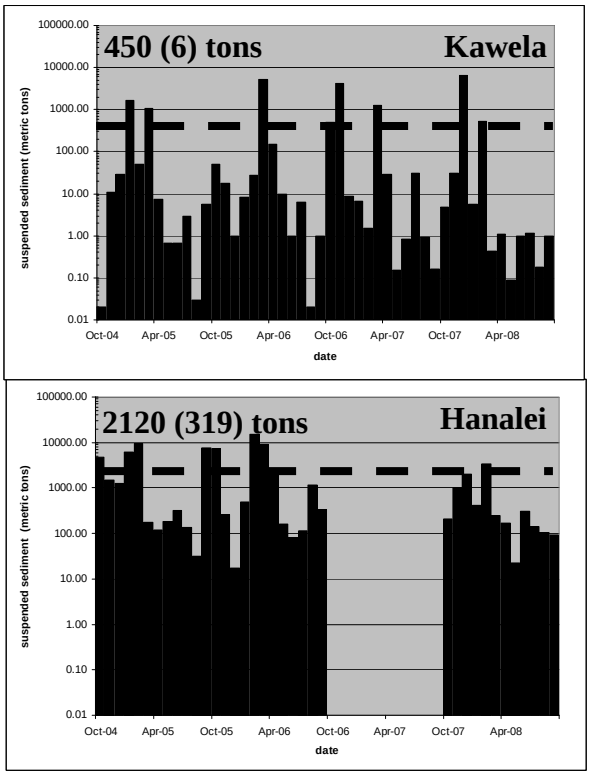

Figure 4. Monthly suspended sediment passing the gages at Kawela and Hanalei. Arithmetic mean monthly values shown by dashed lines, median values in parentheses. Monthly export at Kawela is dominated by winter and spring events. Median values are much lower than those at Hanalei, reflecting more episodic transport in the intermittent stream.

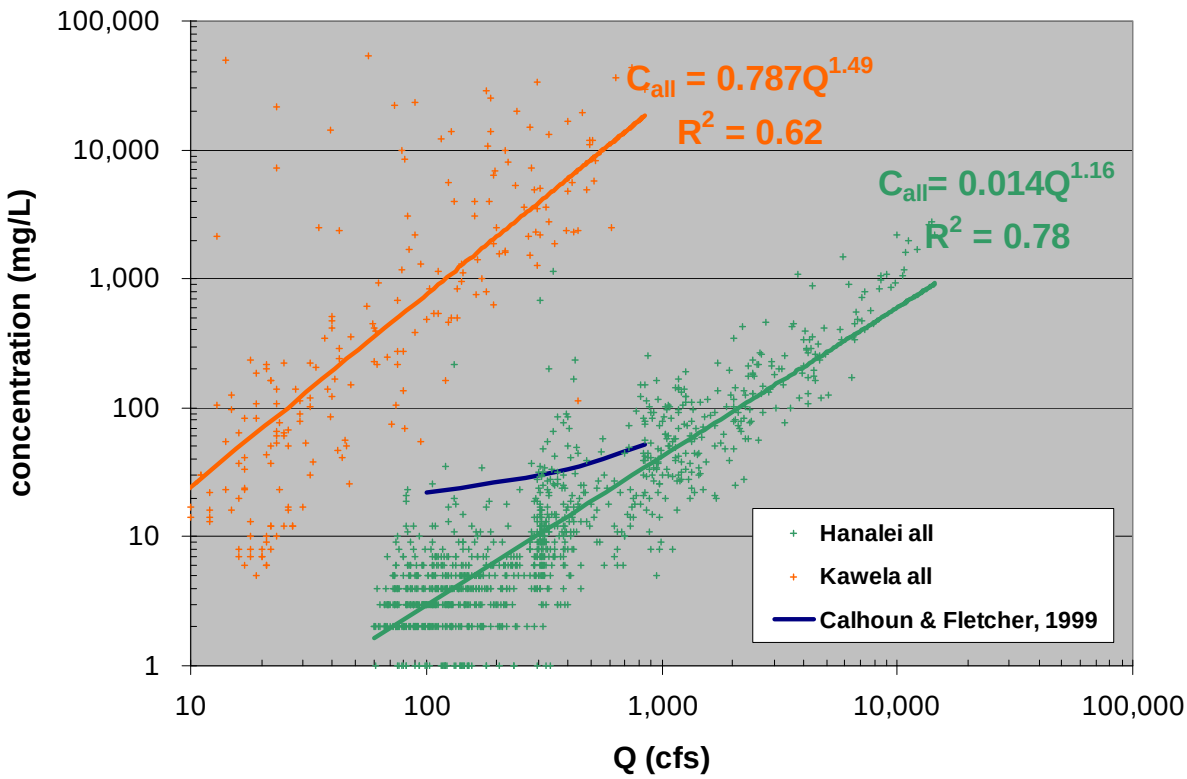

Figure 5. Plot of suspended sediment concentration C (mg/L) vs. instantaneous discharge Q in cubic feet per second (cfs) for all data from Kawela (orange) and Hanalei (green). Ratings curve proposed by Calhoun and Fletcher (1999) based on limited sampling shown as blue line.

Hysteresis curves at Kawela are dominated by clockwise patterns, with very high sediment concentrations (e.g., > 10,000 mg/L) occurring prior to the peak of the hydrograph (e.g., red and yellow curves in Figure 6). These curves lie well outside of the log-log linear trends. At Hanalei, the observed hysteresis curves are much smaller than those observed at Kawela, and lie within the observed log-log linear trends. Hanalei has several prominent counter-clockwise curves (one example is shown by the bold blue line in Figure 6), a pattern that is absent from the Kawela record.

INTERPRETATION

Annual sediment yield in the Hanalei basin (1,360 tons/yr/mi^2,) exceeds the Kawela basin yield (1,020 tons/yr/mi^2) despite the abundance of exposed silts on steep Kawela hillslopes, and the relatively higher sediment concentrations in Kawela per unit stream discharge. We interpret this as a statement about the limited rainfall at Kawela. Given a few more cyclonal storms, it is likely that Kawela's yield could exceed that of Hanalei's.

The steep slope of the Kawela discharge-concentration trend is consistent with the widespread availability of fine tephra, exposed to erosion by rainsplash and overland flow. Rainfall events in excess of ~ 0.5 inches/hour generate runoff that rapidly transports these fines past the gage to the nearshore in a matter of a few hours. So long as the storm is relatively short or does not directly follow a large storm, these runoff events may generate plots that appear log-log linear, or have hysteresis curves that lie close to or within the linear data cloud. At least some storms appear able to reduce the rate of hillslope supply and generate very prominent clockwise hysteresis curves, with large sediment concentrations at comparatively low discharges (e.g., Fig. 6). These storms predate our experimental site, but are likely accompanied by long periods of intense rainfall at mid-slope elevations where much of the exposed tephra deposits occur. These hillslopes are within several miles of the gage, and could quickly produce high

sediment concentration water before the hydrograph peak. As a consequence, sediment concentrations at Kawela can vary by orders of magnitude over an event, leading to hysteresis curves that are much larger than the observed log-log linear trends.

At Hanalei, canopy reduces the rainfall intensities reaching the ground, and the surface is protected by vegetation from erosion by rainsplash and overland flow. We hypothesize that the counter-clockwise pattern observed in some events at Hanalei may record the input of fines by bank failure as river stage declines. We suspect that the clockwise hysteresis curves at Hanalei are smaller in magnitude than those at Kawela because there are no large areas of exposed soil that could generate high-concentration pulses of sediment to the gage. The occurrence of counter-clockwise hysteresis loops is consistent with observations of bank failure that could supply fine sediment to the river late in the hydrograph.

CONCLUSIONS

Suspended sediment monitoring at Kawela Stream, Molokai Island, and Hanalei River, Kauai Island, provides concurrent records of suspended sediment from two diverse watersheds in the Hawaiian Islands. The Hanalei basin has a 3-year averaged suspended sediment yield of 1,360 tons/yr/mi^2. Export of suspended sediment to the nearshore

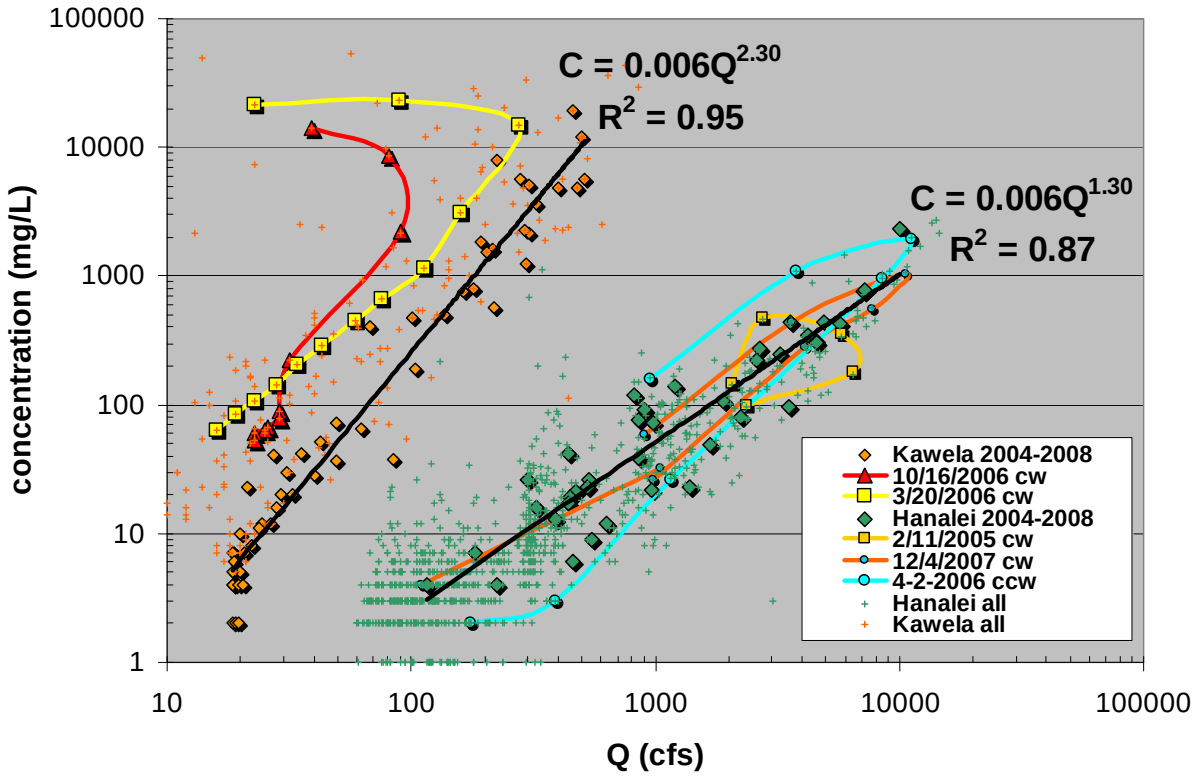

Figure 6. Plot of suspended sediment concentration vs. instantaneous discharge Q in cubic feet per second (cfs) for Kawela and Hanalei, highlighting linear and hysteretic events.. Orange (Kawela) and green (Hanalei) diamonds represent all of the events that are 1) five or more samples taken in a row and 2) follow a log-log linear trend. Red and yellow bold lines represent the two largest recorded hysteresis events on the Kawela Stream, which follow a clockwise (cw) evolution so that the earliest recorded values are in the upper left. Orange lines (clockwise, cw) and blue line (counter-clockwise, ccw) represent the largest recorded hysteresis events in the Hanalei River. Black lines are power law regressions to all linear events from Kawela and Hanalei. The steeper slope of the Kawela power law indicates that runoff has access to more fine sediment in this basin than in Hanalei. The strong hysteresis events in Kawela indicate that sediment supply in this basin can be much reduced during large events. The full data set (small green and orange symbols) increases the scatter because of the addition of many hysteretic events.

is continuous in this perennial river, which drains a heavily vegetated, high-rainfall basin. Basinwide averaged surface lowering rates for soil, saprolite and bedrock are 0.56 mm/yr, 0.44 mm/yr, and 0.18 mm/yr respectively. The arid, sparsely vegetated Kawela basin on Molokai has a 4-year averaged yield of 1,020 tons/yr/mi^2. Export of sediment in this basin is dominated by one to several large storms every year, with long periods of little to no flow and no sediment discharge. Basinwide averaged surface lowering rates for soil, saprolite and bedrock are 0.42mm/yr, 0.33 mm/yr, and 0.13 mm/yr respectively. These rates underestimate local surface lowering, which is likely concentrated in a small fraction of the total basin area.

In Kawela, exposed silt deposits are susceptible to high rainsplash and overland flow erosion rates that generate a discharge-sediment concentration line almost twice as steep as that observed in Hanalei. Clockwise hysteresis curves in Kawela are corresponding much larger, as hillslopes exposed to overland flow can generate very high suspended sediment concentrations before their supply rates decrease over long storms. By contrast, Hanalei basin hysteresis curves all lie within the cloud of log-log linear data. This difference likely reflects that the primary source of fines in Hanalei is from erosion of banks or other channel-proximal deposits, rather than large unvegetated areas..

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