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Measured and predicted sediment yield from a subtropical, heavy rainfall, steep-sided river basin: Hanalei, Kauai, Hawaiian Islands

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Abstract

To determine the sediment yield of the 54.4 km^2 Hanalei River basin, we employ three methods: (1) the Universal Soil Loss Equation (USLE), which uses natural characteristics of the basin such as the amount of rain, slope steepness and length values, and soil types to predict sediment erosion in a basin; (2) the thickness and calibrated radiocarbon age of fluvial deposits cored from the coastal plain; and (3) field measurements of suspended sediment in the river. Method 1 (USLE) provides a model prediction of sediment yield that we test with observational data of methods 2 and 3. Several curves, including one by the US Soil Conservation Service, predict a sediment delivery ratio (measured sediment yield: gross erosion) between approximately 15% and 50%. With 5260 ± 2210 Mg (metric tons) yr^{-1} of suspended sediment in the Hanalei River and 2300 ± 700 Mg yr^{-1} deposited on the coastal plain, however, the delivery of sediment in the Hanalei basin ranged between 45% and 101% of the maximum predicted USLE value (88 ± 103 Mg km^{-2} yr^{-1}). This higher than predicted yield may be the result of mass movement. We are not able to differentiate, however, between erosion and mass movement as the principle agent of denudation. Our measurements indicate a total sediment yield of 140 ± 55 Mg km^{-2} yr^{-1} for the Hanalei Valley.

Keywords: sediment yield; universal soil loss equation; sediment erosion; coastal sediment deposition; suspended sediment; Hawaii

1. Introduction

In the Hawaiian Islands, limited research exists describing the erosion of sediments on a basin or island-wide scale. Denudation of the Kaneohe Bay drainage basin on windward Oahu was examined by bedrock analysis, soil and soil-forming processes, and the concentration of detrital sediment in the bay (Moberly, 1963). Sediment yields from the Makiki, Manoa, and Palolo Valleys of central Honolulu were analyzed using rates of deposition, determined by ^{210}Pb and ^{137}Cs dating techniques, of sediments found in the Ala Wai Canal (McMurtry et al., 1995). Li (1988) calculated island-wide rates of denudation for the islands of Hawaii, Oahu, and Kauai based on measurements of dissolved and suspended sediment concentrations in multiple rivers and groundwater wells around the three islands.

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Here, we determine physical loss of sediment from the Hanalei River basin using observations of floodplain sedimentation and the delivery of suspended sediment to Hanalei Bay. These are, in turn, used to test the predictions of sediment yield by the Universal Soil Loss Equation (USLE). This combination of measured and predicted sediment erosion and deposition has not been previously used in Hawaii, particularly not in non-agricultural wildlands.

2. Geologic setting

The Hanalei River basin, extending north from Mt. Waialeale near the center of the Hawaiian Island of Kauai, receives rainfall volumes that are among the highest on Earth (> 10 m yr^{-1}). The basin is comprised predominantly of steep-sided mountain walls plunging into deep, fluvially-cut gorges. Though heavily vegetated, the steep slopes and high rainfall ensure a steady supply of sediment to the river. At 25.2 km in length and with a drainage area of 54.4 km^2, the Hanalei River is one of the largest rivers in the Hawaiian Islands. Over much of its length, the Hanalei River flows between canyon walls with little or no real floodplain. Below the $\sim$ 61 m (200 ft) contour, however, the canyon begins to widen and the river forms a floodplain over its final 12 km. In its lowest reach, the river traverses

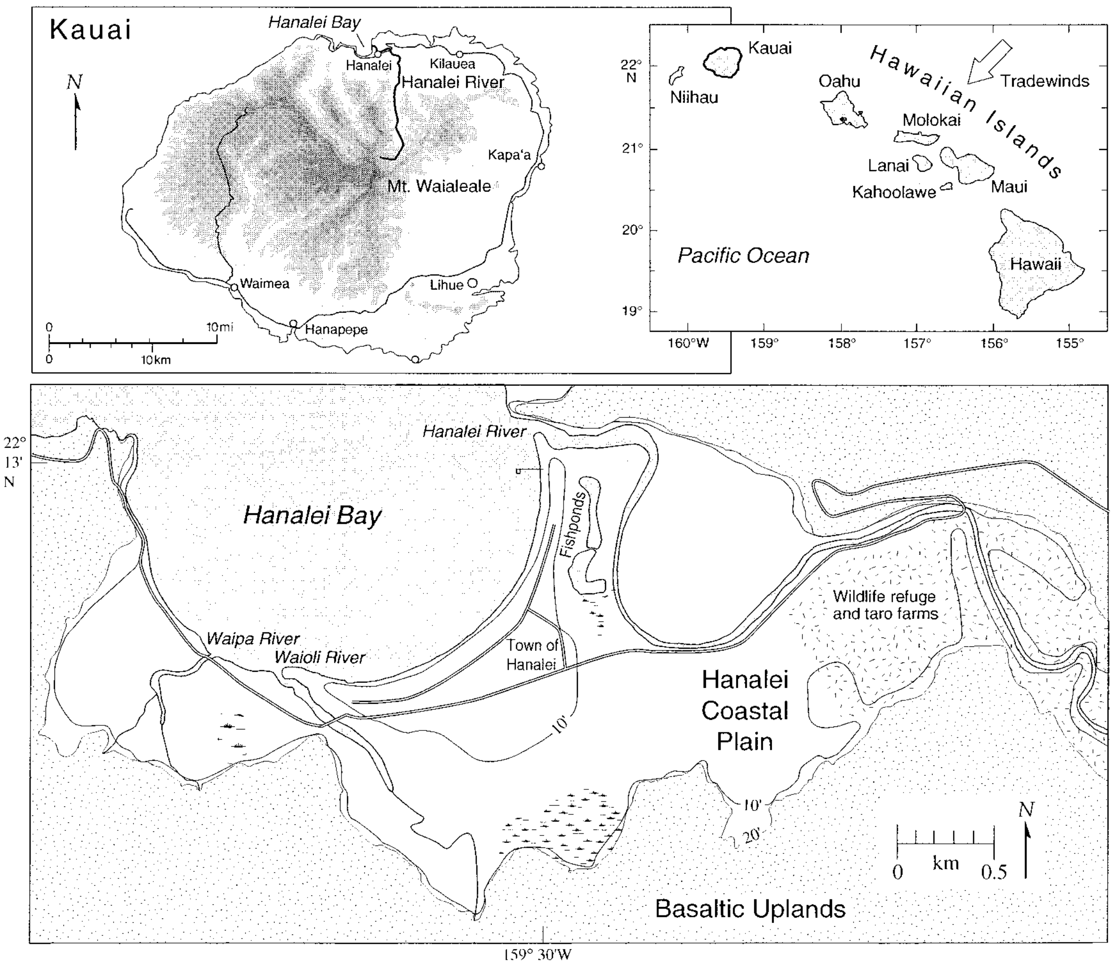

Fig. 1. Map of the Hawaiian Islands, the island of Kauai, and the Hanalei coastal plain on the north shore of Kauai, Hawaii. Also shown are the town of Hanalei, major roads, and areas of disturbed stratigraphy associated with a waterfowl refuge and Hawaiian fishponds. The 10 and 20 ft (3.0 and 6.1 m) contours were obtained from US Army Corps of Engineers contoured orthophotoquads (1:4800).

6.6 km of the Hanalei coastal plain, defined by the ~ 6 m (20 ft) contour, before entering the east side of Hanalei Bay (Fig. 1).

The upper-most sedimentary facies of the coastal plain is a red-brown mud derived from the overbank flow of the Hanalei River (Calhoun and Fletcher, 1996). The top facies is generally underlain by a carbonate sand that is marine or fluvial–marine in origin. This carbonate sand is a relic of former marine influence that we have interpreted as showing net shoreline progradation over the last 4000 years (Calhoun and Fletcher, 1996). The well-dated contact between the marine and fluvial lithosomes provides an excellent base from which to calculate the volume and rate of recent sedimentation deposited by the Hanalei River.

Three general sizes and mechanisms of subaerial mass movement have been identified in the steep valleys in Hawaii. The smallest mechanism, called soil avalanches by Wentworth (1943) and soil slips by Ellen et al. (1993), involves movement of only the top soil and range in size from a few cubic meters up to approximately 1000 m^3. During studies of the Honolulu District of Oahu, Scott (1969) and Ellen et al. (1993) calculated the mean volume of 201 of these slips to be 120 m^3. An average of between 30 and 40 of these soil slips occur each year in this district depending on the number and severity of rain events (Ellen et al., 1993; Peterson et al., 1993). Landslides resulting from the second mechanism, the failure of weathered basalt (saprolite), occur in the Honolulu District approximately once a decade and have volumes in the tens of thousands of m^3 (Peterson et al., 1993). Both of these types of mass movement are related to times of severe rainfall events. The third type of mass movement is massive rock avalanches which occur when unweathered basalt bedrock fails. These are not associated with rainfall events and probably result from gradual undercutting and loss of shear strength in overlying beds. The location of these infrequent massive avalanches has been linked with ash layers in the bedrock and is associated with earthquakes. They may include hundreds of thousands to millions of m^3 of rock and soil (Jones et al., 1984). Analysis of geologic maps (Macdonald et al., 1960), descriptions and maps from the US Soil Conservation Service (1972), and aerial photographs indicates that all three of these types of mass movement described elsewhere in Hawaii do or should be able to occur in the Hanalei Valley.

Several studies (Scott and Street, 1976; Jones et al., 1984; Ellen et al. 1993; Peterson et al. 1993) have described the frequency and volume of mass movement. A few have computed the total volume of denudation from individual valleys or islands (Moberly, 1963; Li, 1988; Hill et al., 1997). Although White (1949) addresses it, this is the first study to quantify denudation of a pristine Hawaiian valley based upon soil erosion.

3. Methods

We utilize several methodologies to determine the sediment yield of the Hanalei watershed. Cores were obtained with a gouge auger at 104 sites throughout the coastal plain to determine subsurface stratigraphy. These were 2.54 cm in diameter and typically between 3 and 7 m in length. Core penetration was limited by sediment density, most often after encountering marine sands. Samples of cored sediments were radiocarbon dated to provide long-term rates of the accumulation of sediment and to determine the transition from marine to fluvial sedimentation. Short-term rates of sedimentation were obtained at three locations by means of short (< 1 m), thick (6.5 cm) cores. The shallowest depth of zero ^{210}Pb activity in each core is used in the calculations of the rates of sedimentation.

Isopach mapping of the coastal plain provides an estimate of the volume of fluvial sediment deposited there. Combining this information with radiocarbon ages at the base of the fluvial lithosome allows the calculation of the annual rate of deposition of the volume of sediment on the coastal plain during the Late Holocene.

Discharge and crest-stage data on the Hanalei River are recorded at two US Geological Survey (USGS) stations. The first is a water-stage recorder located 7.89 km from the river mouth and 10.91 m above mean sea level. At this station, the instantaneous discharge and the crest height are recorded every half hour from water year 1962 to 1994, although only the daily mean discharge is preserved in the long-term record. In addition, from 1962 to 1979, the maximum discharge and crest height for each year are recorded. From 1980 to 1994, every discharge above 261 m^3 s^{-1} (9200 cfs) and its accompanying crest height are recorded. The second station is located 3.86 km above the river mouth on the Highway 56 Bridge near the town of Hanalei. This gage measures only crest-stage and records the maximum crest-heights for water years 1963 through 1994. It uses mean sea level as its datum.

We gathered a record of suspended sediment in the Hanalei River using a USDH 48 hand-held water sampler. Integrated depth (0–100 cm) water samples were collected from the center of the Highway 56 bridge next to the crest-stage gage on 90 consecutive days from January 21 to April 20, 1995, considered the approximate rainy season on Kauai. Approximately 950 ml of water were collected per observation under normal conditions. Five hundred milliliters or less were collected when the water was particularly turbid. We used ~33 kPa (~5 lb) of vacuum to aid in the subsequent filtering of the water samples through a preweighed 0.45 μm filter. The filters were then dried for 48 h at 60°C and the mass measured to the nearest 0.0001 g. Repeated filtrations with distilled and deionized water indicate that the technique is accurate to 0.001 ± 0.0005 g. The mass of the sediment left on the filters was used to calculate the concentration of suspended sediment in g l^{-1} of water discharged by the Hanalei River. This, in turn, was combined with the data for daily discharge from the USGS discharge station to calculate the mass of suspended sediment load of the Hanalei River. Stream discharge was then compared to the measured load of suspended sediment to de-

Table 1
Factors of the USLE[a]

Factor	Value for Hanalei Basin (units)	Source
R (rainfall and runoff)	1070 (100 N h^{-1})	Lo et al. (1985) and NWS rain gage data
K (soil erodibility)	0.148–0.458 (tons per acre per erosion index unit)	US Soil Conservation Service descriptions and Fig. 3 from Wischmeier and Smith (1978)
LS (slope length and steepness)	120 (unitless ratio)	Equations from Foster and Wischmeier (1974) and measurements from USGS topographic maps
C (cover and management)	$1.01 \times 10^{-5} \pm 0.908 \times 10^{-5}$ (unitless ratio)	Fractional Uncertainty Multiplication from Taylor (1982)
P (support practice)	incorporated into *C*	Dissmeyer and Foster (1980)
C subfactors (percentage used in calculation)		
Bare soil (90–100%)	0.03–0.07	Fig. 2 from Wischmeier (1975) and field observations
Canopy (80–90%, 0.5 m understory)	0.34–0.40	Fig. 1 from Wischmeier (1975) and field observations
Soil reconsolidation	0.45	Dissmeyer and Foster (1980)
High organic content	0.7	Dissmeyer and Foster (1980)
Fine roots (80–90%)	0.26–0.32	Fig. 15 from Dissmeyer and Foster (1980) and field observations
Onsite storage (70–90%)	0.10–0.30	Dissmeyer and Foster (1980) and field observations
Steps (80–90%)	0.0112–0.0483	Equations from Foster and Wischmeier (1974), measurements from USGS topographic maps, equations derived from Table 7 of Dissmeyer and Foster (1980), and field observations
Residual binding effect	not used in forest environment	Dissmeyer and Foster (1981)
Contour tillage	not used in forest environment	Dissmeyer and Foster (1981)
A (eroded sediment)	0.3913 ± 0.4571 tons $acre^{-1}$ yr^{-1} or 88.2 ± 102.9 Mg km^{-2} yr^{-1}	Fractional Uncertainty Multiplication from Taylor (1982)

[a] The USLE: $A = R \cdot K \cdot L \cdot S \cdot C \cdot P$; from Wischmeier and Smith (1978).

rive a regression equation. Discharges in the 31.75-year USGS record formed the basis for obtaining a longer-term calculation of suspended sediment output. Although during normal conditions of discharge one sample was taken per day, at times of high discharge, samples were collected throughout the day to more accurately measure the sediment flux of an event. A total of 127 samples were taken from the river.

To characterize the collection site for suspended sediment, five samples were taken from evenly spaced locations laterally across the bridge. Additionally, daily water conductivity and temperature measurements were obtained. The thickness of the fluvial water column and the basal marine wedge in the channel could then be calculated. A 290-g grab sample of sediment from the river bottom was also obtained and described using sieves ranging in size from -1.0 to 4.0ϕ in 0.5ϕ increments.

In addition to these field methods, we used an empirical model, the USLE, to describe the Hanalei basin, model the mass of eroded sediments, and facilitate comparisons with other basins. The factors of the USLE (Table 1) were determined using data from US Soil Conservation Service (1972) soil descriptions, field observations, and tables, graphs, and equations from Foster and Wischmeier (1974), Wischmeier (1975), Wischmeier and Smith (1978), and Dissmeyer and Foster (1980).

4. Results

Late Holocene rates of accumulation of fluvial sediments on the Hanalei coastal plain, covering thousands of years and calculated with radiocarbon dates, range from 0.07 to 3.06 mm yr^{-1} with rates generally highest near river channels and decreasing with distance from the river banks (Fig. 2). Minimum rates are found in the center of the coastal plain far from any immediate source. Short-term sedimentation, measured with short cores, covering less than 150 years, and calculated with ^{210}Pb dating techniques, also indicate a decrease in the rate of sedimentation as the distance from the Hanalei River increases. These short-term rates, 0.82 to 3.09 mm yr^{-1} (Fig. 3), correlate well with calculations of long-term accumulation using radiocarbon.

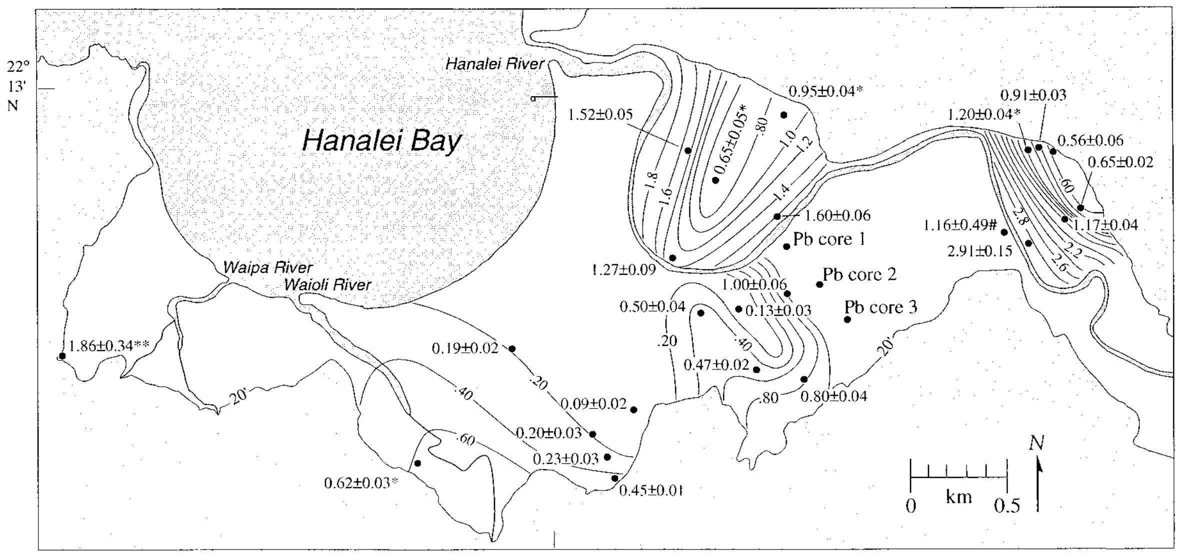

Fig. 2. Sediment accumulation rate in mm yr^{-1} from 7000 years B.P. to the present. Contour interval = 0.20 mm yr^{-1}. All accumulation rates are based on surface to depth interval except where noted. * Cores containing inverted dates. ** Cores with rates derived from a dated interval. #The average of three rates obtained from the core.

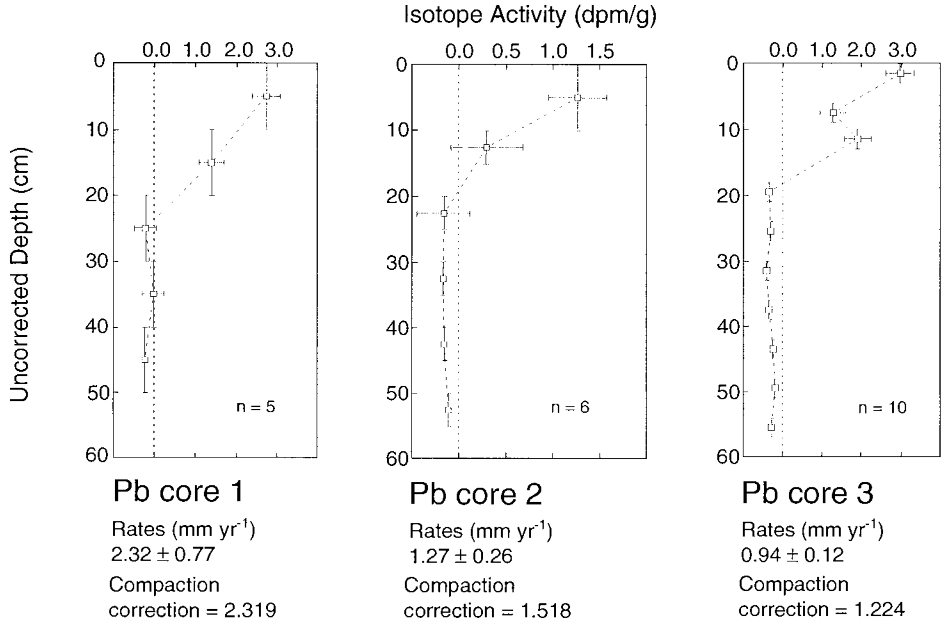

Fig. 3. Profiles of three cores showing depth and lead radioactivity strength of each tested sample. The horizontal errors in many of the samples are smaller than the squares used to show the locations. The locations of these cores on the coastal plain are shown in Fig. 2.

From the isopach map derived from our core data, we estimate that the Hanalei River has deposited 7,520,000 m^3 of sediment on the coastal plain over the past 4000 years. Measurements of 21 dried samples of sediments indicate that the average bulk density is 1.22 ± 0.38 Mg m^{-3} (2σ). Hence, we calculate that the river has deposited $\sim$9,170,000 Mg of sediments on the coastal plain during the last 4000 years, or an average of 2300 ± 700 Mg yr^{-1} of sediment.

At the bridge sampling site, a wedge of marine water was present during 76% of the sampling days with an average thickness of 1.54 m and a maximum thickness of 2.37 m. The river flowing over this wedge averaged 1.52 m thick with a minimum of 0.60 m. During times of increased flow, the marine wedge was pushed down river by the fluvial discharge. Several days of low flow were needed to allow the wedge to return to its original thickness. Bottom sediments immediately upriver from the bridge consist of moderately sorted, very coarse, rounded, basalt sands and granules with a mean ϕ size of -0.23, a standard deviation of 0.90ϕ, and skewness of 0.53ϕ. Suspended sediment samples from the four locations to either side of midchannel were found to contain slightly less suspended sediment than simultaneously collected samples from the standard midchannel station. The mass of sediment obtained from the side locations was, however, well within the range normally found at the midchannel station.

To calculate the mass of suspended sediment carried by the Hanalei River, we regressed the discharge history against our measurements of the concentration of suspended sediments. Only discharges greater than 2.83 m^3 s^{-1} (100 cfs) were used in the comparison to eliminate the random variability of concentrations found at extremely low discharge levels. A regression of this relationship (Fig. 4) yields: $Y = 1.39X + 17.98$ where $Y =$ suspended sediment concentration (g m^{-3}) and $X =$ river discharge in m s^{-1}. The average daily mean discharge is 6.38 m^3 s^{-1} (225 cfs) with a range of 2.83 m^3 s^{-1} (100 cfs) to 24.1 m^3 s^{-1} (852 cfs). This relationship has a correlation coefficient (r) of 0.76, a probability (p) value of less than 0.001, and the standard error of estimate is 5.53 g m^{-3}. The mean daily discharge of each month from January 1963 through September

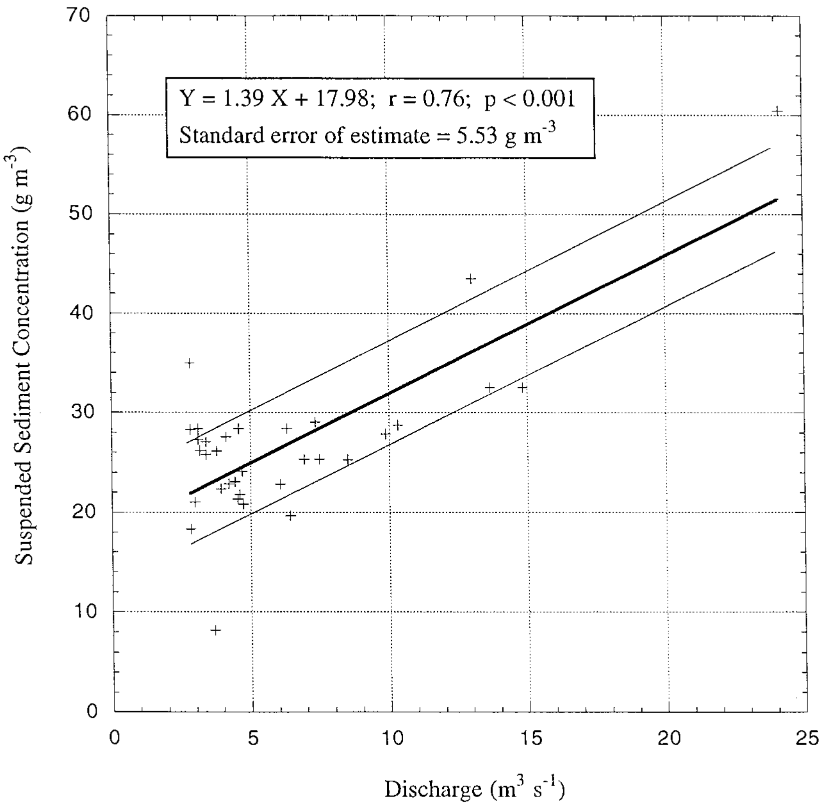

Fig. 4. Discharge vs. suspended sediment of the Hanalei River. Discharge ranges between 2.83 m^3 s^{-1} (100 cfs) and 24.1 m^3 s^{-1} (852 cfs). Data were collected between January 21 and April 20, 1995. Bold line shows the equation curve and the two thin lines show the standard error of estimate of 5.53 g m^{-3}.

1995 was calculated and averaged with the other monthly mean discharges from a given year. The 31.75 years of data shows that 5260 ± 2210 Mg yr^{-1} of sediment are released into Hanalei Bay by the Hanalei River.

The USLE predicts gross erosion in short tons (2000 lb) per acre per year. Using fractional uncertainty multiplication (Taylor, 1982) on the USLE factors yields a prediction that 0.39 ± 0.46 tons $acre^{-1}$ yr^{-1} of sediment will be eroded from the Hanalei basin (Table 1). Converted to metric, the USLE predicts that the 54.4 km^2 Hanalei watershed will release a total of 4800 ± 5600 Mg sediment yr^{-1}. By design of the USLE, this figure is total erosion, which includes the sediment that is eroded and is carried via the river to the sea as well as the sediment that is redeposited a few meters downslope from where it is eroded.

5. Discussion

Li (1988) calculated a maximum rate of physical denudation of 400 ± 200 Mg km^{-2} yr^{-1} for the island of Kauai. In the Hanalei valley, this converts to $21{,}760 \pm 10{,}880$ Mg yr^{-1}. A minimum rate was not calculated. Our measurements of the sediment deposited on the Hanalei coastal plain combined with the suspended sediment in the river suggest that 4650–10,470 Mg yr^{-1} are being removed from the upper valley. Our measurements of Hanalei, despite being on the windward side of the island, should not

Table 2
Comparison of the rates of physical erosion in Hawaii

Author	Island	Area drained (km^2)	Sediment yield ($Mg\ km^{-2}\ yr^{-1}$)	Sediment load ($Mg\ yr^{-1}$)	Denudation ($mm\ yr^{-1}$)	Method
This paper	Kauai	54.4	140 ± 55	7560 ± 2910	0.07–0.16	fluvial yield
Hill et al. (1997)	Oahu	10.4	330 ± 130	3400 ± 1350	0.30–0.70	fluvial yield
			200 ± 100	2080 ± 1040	0.1–0.3	aerosol quartz and ^{137}Cs concentrations
McMurtry et al. (1995)	Oahu	42.9	61.2[a]	2630	0.08	^{210}Pb and ^{137}Cs concentrations in sediments
Ellen et al. (1993)	Oahu	Koolau Range	–	–	0.02–0.15[b]	K–Ar dates for original Koolau volcano surface and sequential digital simulations of erosional development
Li (1988)	Kauai	Island wide	? -400 ± 200	–	0.18 ± 0.08	cation and SiO_2 concentrations
Li (1988)	Oahu	Island wide	60–300	–	0.10 ± 0.06	in rivers and groundwater
Scott and Street (1976)	Oahu	7	760 ± 621	5290 ± 4350[c]	0.16–0.86	field measurement of soil avalanche scars
Moberly (1963)	Oahu	82	340 ± 50[d]	27900 ± 4100	0.13	dissolved calcium
Wentworth (1943)	Oahu	38.8	690 ± 215	26800 ± 8350[e]	0.76	estimate number of slides and their volumes

[a] Adapted from McMurtry et al. (1995).
[b] Adapted from Fig. 5 in Ellen et al. (1993).
[c] Adapted from Scott and Street (1976) assuming a soil density of 1.22 ± 0.38 Mg m^{-3}.
[d] Adapted from Moberly (1963) based on rates from removal of dissolved weathering products, and assuming basalt density of 2.60 ± 0.35 Mg m^{-3}.
[e] Adapted from Wentworth (1943) assuming a soil density of 1.22 ± 0.38 Mg m^{-3}.

be equal to the maximum rates of Li (1988) for two reasons. First, we do not include measurements of mass movement as Li (1988) does. Mass movement is considered to be a significant method of sediment movement on steep mountain slopes in the Hawaiian Islands (Scott and Street, 1976). Second, we were not able to include any high discharge events of the Hanalei River because the sampling interval covers an El Niño year, known to be a period of reduced rainfall in the Hawaiian Islands. Given the limited temporal period of measurement and other constraints previously discussed, the measured values should be considered minimum estimates.

McMurtry et al. (1995) calculated 2630 Mg yr^{-1} of detrital sediment deposited in the Ala Wai Canal on the island of Oahu (Table 2). The canal drains 42.9 km^2 of urbanized central Honolulu and nearby steep undeveloped mountains. This results in a sediment yield of 61.2 Mg km^{-2} yr^{-1} from the Ala Wai drainage basin compared to 140 ± 55 Mg km^{-2} yr^{-1} in the Hanalei valley. The drier climate and heavy urbanization of central Honolulu are likely to be contributing factors to the lower sediment yield from the Oahu basins. Values of sediment yield from McMurtry et al. (1995) are at the lower end of the range (60–300 Mg km^{-2} yr^{-1}) predicted for Oahu by Li (1988). Li (1988) does not give a minimum rate of denudation for Kauai, but our rate (140 ± 55 Mg km^{-2} yr^{-1}) is substantially below the Kauai maximum of Li (1988) of 400 ± 200 Mg km^{-2} yr^{-1} and well above his minimum rate of denudation of 60 Mg km^{-2} yr^{-1} predicted for the islands of Hawaii and Oahu. High end yield estimates by Wentworth (1943) and Scott and Street (1976) are based on direct field measurements of mass movement scars. They reflect a maximum rate of denudation and may indicate that portions of soil avalanches are stored low in the valley for periods longer than a thousand years.

Comparisons of the rates of sediment deposition on the Hanalei coastal plain with other rates of deposition in various environments from around the world are shown in Table 3. Hanalei has a low rate of deposition relative to other depositional environments, but has a range similar to those found on other floodplains. The high rates found by Good-

Table 3
Rates of sediment deposition from various environments

Location	Rate of Deposition (mm yr^{-1})	Author (year)	Method
Open water (oceans, bays, lakes)			
Northeastern Skagerrak (Norway)	0.8–11.0	Van Weering et al. (1993)	^{210}Pb and ^{137}Cs
Barmouth Bay (Wales)	2.3–3.1	Larcombe and Jago (1994)	Radiocarbon, seismic profiles (?)
Lillooet Lake (British Columbia, Canada)	7.0–28.5	Desloges and Gilbert (1994)	varves, seismic profiles, ^{137}Cs
Skagerrak and Oslofjord (Norway)	1.0–11.0	Pederstad et al. (1993)	seismic profiles, zinc presence
Estuaries and other confined bodies of water			
Illinois River (IL, USA)	2.0–79.2	Bhowmik and Demissie (1989)	bathymetry measurements (?)
Hamble estuary (England)	4.0–8.4	Cundy and Croudace (1995)	^{210}Pb and ^{137}Cs
Mawddach estuary (Wales)	~ 82.0	Larcombe and Jago (1994)	Radiocarbon, seismic profiles (?)
Ala Wai Canal (HI, USA)	20–220	McMurtry et al. (1995)	^{210}Pb and ^{137}Cs
Paleolakes and wetlands (Mangaia, Cook Islands)	0.58–12.1	Ellison (1994)	Radiocarbon
Floodplains			
Hanalei coastal plain (HI, USA)	0.07–3.06	Calhoun and Fletcher (this paper)	Radiocarbon
Hanalei coastal plain (HI, USA)	0.82–3.09	Calhoun and Fletcher (this paper)	^{210}Pb
Ganges delta (Bangladesh)	0.3–4.0	Umitsu (1993)	Radiocarbon
Colorado River (TX, USA)	0.24–3.12	Blum and Valastro (1994)	Radiocarbon
Nile delta (Egypt)	0.51–19.0	Goodfriend and Stanley (1996)	Radiocarbon, amino acid racemization, stable isotope analysis

friend and Stanley (1996) on the Nile River delta could be the result of being measured in a lake on the floodplain and, therefore, more closely resemble those in the open water section of the table. Despite the differences in characteristics in size and area, the Hanalei River (length: 25.2 km; area: 54.4 km^2), the Colorado River of Texas (1400 km and 110,000 km^2), and the Ganges River of India and Bangladesh (2500 km and 952,000 km^2) (Showers, 1979) have remarkably similar rates of sediment deposition (Table 3). The Ganges River is among the largest continental rivers in the world, draining high mountainous terrain and includes seasonal monsoon and snowmelt runoff, whereas the Colorado River drains the semi-arid plains of west and central Texas accustomed to episodic heavy rains before crossing the more humid Texas gulf coast region. The Hanalei River valley is characterized by steep, humid, forested mountainsides where mass movement and soil erosion, encouraged by copious volumes of rainfall, are significant means of sediment mobilization.

Because the long-term rates of sediment accumulation and the short-term rates of sedimentation overlap on the Hanalei floodplain, compaction and erosion of the fluvial coastal plain sediments are not considered to be significant processes. As a result, the volume of fluvial sediment present on the modern coastal plain represents the total deposited during the last 4000 years. Prior to 4000 years ago, Hanalei Bay covered much of the modern coastal plain and limited significant fluvial deposition to the extreme eastern portion (Calhoun and Fletcher, 1996). These Middle to Late Holocene fluvial sediments represent the deposition of suspended sediment during flood conditions, a major constituent of the sediment budget missed by the daily observations of suspended sediment. Neither the 2300 ± 700 Mg yr^{-1} deposited on the coastal plain nor the measured 5260 ± 2210 Mg yr^{-1} of suspended sediment lost to the bay, however, account well for the large volumes of suspended sediment which pass completely through the Hanalei River system and into the bay during extremely high discharge events. One high discharge event was sampled in the field, but it is considered a bankfull event and cannot accurately be compared with the massive discharges that reach heights of up to 2.5 m above flood stage. Even this minimal event, however, contained nearly seven times the concentration of suspended sediment that would be predicted for such a discharge based on interpolations from normal flow conditions. This high concentration of suspended sediment shows that high discharge events cannot be adequately explained by simple extrapolation from normal flow discharges. These events, which range in frequency from zero to five events per year, have yet to be adequately sampled, and, as a result, the contribution of sediment to the bay, though almost certainly significant, must remain speculative.

The USLE was designed for and empirically tested on the gently sloping, deep soiled, agricultural fields of the American midwest and eastern seaboard. In this study, it was applied to the steep, thin soiled, wildlands of the Hanalei Valley. This study may, therefore, serve as a test of the validity of the USLE in such an environment as well as the applicability of the similar Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975) and the Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1994). The use of these equations would greatly simplify the field measurements and calculations of sediment loss from the valley because of individual high-intensity storms in addition to long-term erosion.

The USLE calculates the total mass of sediments eroded from a specific area. Most drainage basins the size of Hanalei have sediment delivery ratios (measured sediment yield: gross erosion) of 15% to 50% (Walling, 1994) which means the erosion predicted by the USLE will be approximately two to seven times the sediment yield. In the case of the Hanalei Valley however, the measured value (7560 ± 2910 Mg yr^{-1}) is 45% to 101% of the maximum USLE predictions (4800 ± 5600 Mg yr^{-1}). This is not an entirely unexpected result. The consistently steep mountainsides and general lack of a floodplain in the Hanalei Valley results in few areas for the systematic redeposition of eroded sediments. Additionally, because the USLE was set up to calculate only sheet and rill erosion, the locally important process of mass movement is not included in the calculation. Mass movement will increase the measured sediment yield, but not effect the results of the USLE.

With the exception of factor C, which is several orders of magnitude lower than is normally calculated, all factors of the USLE fit within their individual expected ranges. Usually C values smaller than 1×10^{-3} are considered too small to have been accurately measured (El-Swaify, personal communication, 1996). Despite this, higher 'normal' C values would render the final calculation far too high to be of any practical use. Additionally, the use of a lower than 'normal' C value in Hawaii is consistent with the findings of Cooley and Williams (1985), and the C value was calculated using the same equations and graphs that would be used on any forested land (Table 1 and Fig. 5) (Dissmeyer and Foster, 1980).

With a calculation of 4800 ± 5600 Mg yr^{-1} of sediment erosion, the USLE appears at first to reasonably reflect the physical characteristics of the Hanalei Valley. Erosion, however, is not the sole source of soil loss from the valley. Mass movement also contributes to soil loss and must be addressed.

Mass movement has long been recognized as an important process in steep valleys of Hawaii (Stearns and Vaksvik, 1935; Wentworth, 1943; White, 1949; Scott and Street, 1976; Ellen et al., 1993; Peterson et al., 1993; Hill et al., 1997). Several of the more recent authors (Scott and Street, 1976; Ellen et al., 1993; Peterson et al., 1993) have attempted to quantify the volume of denudation because of mass movement. Moberly (1963), Li (1988) and Hill et al. (1997) all quantify the total volume lost from an area, but do not divide the losses by type. Between 15% and 50% of the maximum predicted gross erosion (10,400 Mg yr^{-1}), or 1560 to 5200 Mg yr^{-1},

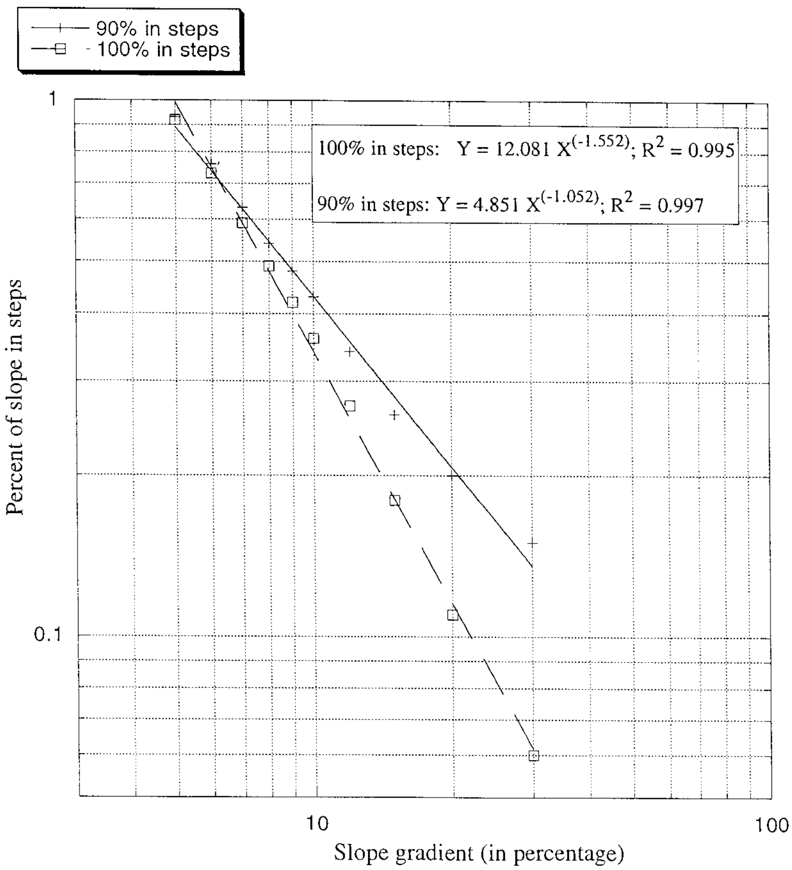

Fig. 5. Percent of slope in steps vs. slope gradient, in percentage. Curves are used to derive steps subfactor of C. Estimates of the percentage of slope that are stepped range between 90 and 100%, while estimates of slope gradient, in percentage, are 80 to 90%. The data points are from Table 7 of Dissmeyer and Foster (1980).

should be eroded from the valley (Walling, 1994). If mass movement does account for the apparent excess sediment found in the Hanalei River and coastal plain, the difference between the total measured sediment (4650–10,470 Mg yr^{-1}) and the eroded sediment (1560–5200 Mg yr^{-1}) is the result of mass movement. The result is that between 0 and 8910 Mg yr^{-1} appear to be removed from the Hanalei Valley by mass movement. It is apparent from comparing the total measured yield, the expected volume of mass movement, and the expected volume of erosion, that the ability to differentiate denudation processes in the Hanalei Valley is not precise enough to warrant practical application.

From the measured yield of 7560 ± 2910 Mg yr^{-1}, a total denudation rate of 0.07–0.16 mm yr^{-1} may be calculated for the 54.4 km^2 Hanalei Valley. This agrees very well with the rates calculated by others (Table 2). It may be surprising to find such good agreement given the direct influence of total rainfall on sediment yield (Scott and Street, 1976; Ellen et al., 1993) and the much higher rainfall volumes in the Hanalei Valley.

6. Conclusions

From field data, we calculate that 7560 ± 2910 Mg sediment yr^{-1}, or 140 ± 55 Mg km^{-2} yr^{-1}, are removed from the upper Hanalei River valley by the river. This is higher than the sediment yield from three central Honolulu drainage basins (McMurtry et al., 1995) as is to be expected because of the lower rainfall and higher degree of urbanization found in the Honolulu watersheds. It also fits within the expected range for Kauai based on the measurements and calculations of Li (1988).

As the rates of deposition indicate, 'overbank' events on the Hanalei River are a common and important characteristic of the river. While these events may presently be described as yearly averages by what they have left behind (i.e. deposited sediments), 'overbank' events cannot yet be individually characterized in terms of frequency and magnitude. It is in these terms that the river must be described to be of practical use for land use managers.

We used the USLE in an effort to test the validity of its assumptions in an environment significantly different from that for which it was developed. If the equation was able to describe erosion in the valley, other equations with similar assumptions, such as the RUSLE and MUSLE, could be used in the valley and greatly simplify the fieldwork necessary to describe the 'overbank' events of the Hanalei River. The measured sediment yield is 45% to 101% of the maximum predicted rate of erosion of 4800 ± 5600 Mg yr^{-1}. The higher than expected sediment delivery ratio may be interpreted to show the importance of mass movement in Hanalei Valley but which is not accounted for by the USLE. Additionally, when the important process of mass movement is addressed, it becomes apparent that we are not yet able to differentiate sediment movement because of erosion and mass movement. As a result, the equation provides a description of sediment erosion that does not appear to be practical.

Calculations show that approximately 30% of the yearly sediment arriving at the coastal plain (7560 ± 2910 Mg) is deposited. The remaining 70% passes through and is discharged into the ocean. Because of biases inherent in the field measurements, more accurate and detailed observations of high discharge events are likely to lower the percentage of total sediment deposited on the coastal plain by increasing the measured volume of sediment passing through the Hanalei River system to the ocean.

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