

1 **TITLE:**

2 **Contributions of human activities to suspended sediment yield during storm events**
3 **from a small, steep, tropical watershed**

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8 **ABSTRACT**

9 Suspended sediment concentrations (SSC) and yields (SSY) during storm and non-storm periods,
10 2012-2014, were measured from undisturbed and human-disturbed portions of a small (1.8 km²),
11 mountainous watershed that drains to a sediment-stressed coral reef. Event-wise SSY (SSY_{EV})
12 was calculated for 142 storms from measurements of water discharge (Q), turbidity (T), and SSC
13 measured downstream of three key sediment sources: undisturbed forest, an aggregate quarry,
14 and a village. SSC and SSY_{EV} were significantly higher downstream of the quarry during both
15 storm- and non-storm periods. The human-disturbed subwatershed (5.2% disturbed) accounted
16 for an average of 71-87% of SSY_{EV} from the total watershed, and was estimated to increase
17 loads to the coast by 3.9x over natural background. Specific SSY (mass/area) from the disturbed
18 quarry area was 49x higher than from natural forest compared with 8x higher from the village
19 area. Similar to mountainous watersheds in semi-arid and temperate climates, SSY_{EV} from both
20 the undisturbed and disturbed watersheds correlated closely with maximum event discharge
21 (Q_{max}), event Total precipitation and event Total Q, but not with a precipitation Erosivity Index.
22 Best estimates of annual SSY varied from 45-68 tons/km²/yr from the undisturbed subwatershed,

350-441 tons/km²/yr from the human-disturbed subwatershed, and 200-247 tons/km²/yr from the total watershed. Sediment yield was very sensitive to disturbance; the quarry covers 1.1% of the total watershed area, but contributed 36% of SSY_{EV}. Given the large distance to other sources of building material, aggregate mining and associated sediment disturbance may be a critical sediment source on remote islands in the Pacific and elsewhere. Identification of sediment hotspots like the quarry using rapid, event-wise measures of suspended sediment yield will help efforts to mitigate sediment loads and restore coral reefs.

Keywords:

Suspended sediment yield, volcanic islands, land use, storm events, coastal sediment load, American Samoa

1. Introduction

Human disturbance including deforestation, agriculture, roads, mining, and urbanization alter the timing, composition, and amount of sediment loads to downstream ecosystems (Syvitski et al., 2005). Increased sediment loads can stress aquatic ecosystems downstream of impacted watersheds, including coral reefs, by decreasing light for photosynthesis and increasing sediment accumulation rates (Fabricius, 2005; Storlazzi et al., 2015). Anthropogenic sediment disturbance can be particularly high on volcanic islands in the humid tropics, where erosion potential is high due to high rainfall, extreme weather events, steep slopes, and erodible soils (Milliman and Syvitski, 1992). Sediment yield in densely-vegetated watersheds can be particularly sensitive to land clearing, which alters the fraction of exposed soil more than in sparsely-vegetated regions. The steep topography and small floodplains on small volcanic islands further limits sediment storage and the buffering capacity of the watershed against increased hillslope sediment supply

(Walling, 1999). Such environments characterize volcanic islands in the South Pacific where many coral reefs are sediment-stressed (Fallon et al., 2002; Hettler et al., 1997; Rotmann and Thomas, 2012).

A large proportion of sediment yield can originate from relatively small, disturbed fractions of the watershed, suggesting management should focus on erosion hotspots. In the grazing-disturbed Kawela watershed on Molokai, Hawaii, most of the sediment originated from less than 5%, and 50% of the sediment originated from only 1% of the watershed (Risk, 2014; Stock et al., 2010). Unpaved roads covering 0.3-0.9% of the watershed were the dominant sediment source on St. John in the Caribbean, and increased sediment yield to the coast by 5-9x relative to undisturbed watersheds (Ramos-Scharrón and Macdonald, 2007). In the U.S. Pacific Northwest, most road-generated sediment originated from just a small fraction of unpaved roads (Gomi et al., 2005; Henderson and Toews, 2001; Megahan et al., 2001; Wemple et al., 1996), and heavily used roads generated 130x as much sediment as abandoned roads (Reid and Dunne, 1984).

Sediment management requires linking changes in land use to changes in sediment yields at the watershed outlet (Walling and Collins, 2008). A sediment budget quantifies sediment movement from key sources like hillslope erosion, channel-bank erosion, and mass movements, to its eventual exit from a watershed (Rapp, 1960). Walling (1999) used a sediment budget to show that sediment yield from watersheds can be insensitive to land use change and erosion management due to high sediment storage capacity on hillslopes and in the channel. Sediment yield from disturbed areas can also be large but relatively unimportant compared to high yields from undisturbed areas. While a full description of all sediment production and transport processes are of scientific interest, the sediment budget can be simplified since most applications

require only the order of magnitude or relative importance of processes be known (Slaymaker, 2003). Reid and Dunne (1996) argue a management-focused sediment budget can be developed quickly where the problem is clearly defined and the management area can be divided into homogenous sub-units.

Knowledge of suspended sediment yield (SSY) under both natural and disturbed conditions on most tropical, volcanic islands remains limited, due to the challenges of in situ monitoring in these remote environments. Existing models are mainly designed for agricultural landscapes, which are not well-calibrated to the physical geography of steep, tropical islands, and ignore important processes like mass movements (Calhoun and Fletcher, 1999; Ramos-Scharrón and Macdonald, 2005; Sadeghi et al., 2007). Developing models that predict SSY from small, mountainous catchments is a significant contribution for establishing baselines for change-detection, and improving regional-scale sediment yield models (Duvert et al., 2012).

Traditional approaches to quantifying human impact on sediment budgets include comparison of total annual yields (Fahey et al., 2003) and sediment rating curves (Asselman, 2000; Walling, 1977). These approaches are complicated by interannual climatic variability and hysteresis in the discharge-sediment concentration relationship (Kostaschuk et al., 2002; Stock and Tribble, 2010). Sediment yield can be highly variable over various time scales, even under natural conditions. At geologic time scales, sediment yield from a non-steady-state watershed may decrease as it reaches equilibrium, or sediment contributions from subwatersheds may change with time (Ferrier et al., 2013; Perroy et al., 2012). At decadal scales, cyclical climatic patterns like El Nino-Southern Oscillation events or Pacific Decadal Oscillation can significantly alter sediment yield from undisturbed watersheds (Wulf et al., 2012).

SSY generated by storm events of the same magnitude can be used to compare the contribution of subwatersheds to total SSY (Zimmermann et al., 2012), determine temporal changes in SSY (Bonta, 2000), and relate SSY to various precipitation or discharge variables ("storm metrics") (Basher et al., 2011; Duvert et al., 2012; Fahey et al., 2003; Hicks, 1990). Event-wise SSY (SSY_{EV}) may correlate with storm metrics such as Total precipitation, the Erosivity Index (EI) (Kinnell, 2013), or Total discharge, but the best correlation has consistently been found with maximum event discharge (Q_{max}). Several researchers have hypothesized that Q_{max} integrates the hydrological response of a watershed, making it a good predictor of SSY_{EV} in diverse environments (Duvert et al., 2012; Rankl, 2004). High correlation between SSY_{EV} and Q_{max} has been found in semi-arid, temperate, and sub-humid watersheds in Wyoming (Rankl, 2004), Mexico, Italy, France (Duvert et al., 2012), and New Zealand (Basher et al., 2011; Hicks, 1990), but this approach has not been attempted for steep, tropical watersheds on volcanic islands.

The anthropogenic impact on SSY_{EV} may vary by storm magnitude, as documented in Pacific Northwest forests (Lewis et al., 2001). As storm magnitude increases, water yield and/or SSY_{EV} from natural areas may increase relative to human-disturbed areas, diminishing anthropogenic impact relative to the natural baseline. While large storms account for most SSY under undisturbed conditions, the disturbance ratio (DR) may be highest for small storms, when background SSY_{EV} from the undisturbed forest is low and erodible sediment from disturbed surfaces is the dominant source (Lewis et al., 2001). For large storms, mass movements and bank erosion in undisturbed areas can increase the natural background and reduce the DR for large events.

This study uses in situ measurements of precipitation (P), water discharge (Q), turbidity (T) and suspended sediment concentration (SSC) to accomplish three objectives and answer the following research questions:

- 1) Quantify suspended sediment concentrations (SSC) and yields (SSY) at the outlets of undisturbed and human-disturbed portions of Faga'alu watershed during storm and non-storm periods.

Research questions: How does SSC vary between storm and non-storm periods? How much has human disturbance increased SSY during storm events? Which human-impacts dominate the anthropogenic contribution to SSY?

- 2) Develop an empirical model to predict SSY_{EV} from an easily-monitored discharge or precipitation metric.

Research questions: Which storm metric is the best predictor of SSY_{EV} : Total event precipitation, precipitation Erosivity Index (Kinnell, 2013), Total event discharge, or maximum event discharge? How does human-disturbance to SSY vary with storm size?

- 3) Estimate annual SSY using the measurements from Objective 1, and modeling results from Objective 2.

Research questions: How does SSY from Faga'alu compare to other volcanic tropical islands and disturbed watersheds.

2. Study Area

Faga'alu watershed is located on Tutuila (14S, 170W), American Samoa, which is comprised of steep, heavily forested mountains with villages and roads mostly confined to the

flat, coastal areas. The mean slope of Faga'alu watershed is 0.53 m/m and total relief is 653 m. The coral reef in Faga'alu Bay is highly degraded by sediment (Fenner et al., 2008) and Faga'alu watershed was selected by the US Coral Reef Task Force (USCRTF) as a Priority Watershed for conservation and remediation efforts (Holst-Rice et al., 2015).

The administrative boundary of Faga'alu includes the watersheds of the main stream (1.78 km²) and several small ephemeral streams that drain directly to the bay (0.63 km²) (grey dotted boundary in Figure 1, "Admin."). Faga'alu watershed is drained by the main stream, which runs ~3 km from Matafao Mtn. to Faga'alu Bay (area draining to FG3 in Figure 1, "Total" watershed). The Total watershed can be divided into an undisturbed, Upper watershed (area draining to FG1, "Upper"), and a human-disturbed, Lower watershed (area draining to FG3, "Lower"). The Lower watershed can be further subdivided to isolate the impacts of an aggregate quarry (area draining between FG1 and FG2, "Lower_Quarry") and urbanized village area (area draining between FG2 and FG3, "Lower_Village") (Figure 1).

Faga'alu occurs on intracaldera Pago Volcanics formed about 1.20 Mya (McDougall, 1985). Soil types in the steep uplands are rock outcrops (15%) with well-drained Lithic Hapludolls ranging from silty clay to clay loams 20-150 cm deep (Nakamura, 1984). Soils in the lowlands include a mix of deep (>150 cm), well drained very stony silty clay loams, and poorly drained silty clay to fine sandy loam along streams and valley bottoms.

2.1 Climate

Annual precipitation in Faga'alu watershed is 6,350 mm at Matafao Mtn. (653 m m.a.s.l.), 5,280 mm at Matafao Reservoir (249 m m.a.s.l.) and ~3,800 mm on the coastal plain (Craig, 2009; Dames & Moore, 1981; Perreault, 2010; Tonkin & Taylor International Ltd., 1989; Wong, 1996). There are two rainfall seasons: a drier winter from June through September that accounts

for 25% of annual precipitation, and a wetter summer from October through May (Perreault, 2010; data from USGS rain gauges and Parameter-elevation Relationships on Independent Slopes Model (PRISM) Climate Group (Daly et al., 2008)). While total P is lower in the drier season, large storms are still observed. At 11 sites around the island, 35% of annual peak flows occurred during the drier season (1959-1990) (Wong, 1996).

2.2 Land Cover and Land Use

2.2.1. *Vegetation, agriculture, and urban areas*

The predominant land cover in Faga'alu watershed is undisturbed vegetation on the steep hillsides (94.8%), including forest (85.7%) and scrub/shrub (9.0%) (Table 1). The Upper watershed is dominated by undisturbed rainforest on steep hillslopes, with no human disturbance. The Lower subwatershed has steep, vegetated hillslopes and a relatively small flat area in the valley bottom that is urbanized (3.2% "High Intensity Developed" in Table 1). A small portion of the watershed (0.9%) is developed open space, mainly landscaped lawns and parks. Agricultural area includes small household gardens and small areas of banana and taro on the steep hillsides, classified as grassland (0.2% GA, Table 1) due to high fractional grass cover. Most unpaved roads are stabilized with compacted gravel and do not appear to be a major sediment source (Horsley-Witten, 2012).

<Table 1 here please>

2.2.2 *Aggregate quarry and reservoirs*

An aggregate quarry covering 1.6 ha has been in continuous operation since the 1960's (Latinis et al., 1996) and accounted for nearly all of the bare land in Faga'alu watershed (1.1%) (Table 1). Sediment was discharged directly to Faga'alu stream until 2011, when quarry

operators installed silt fences and small settling ponds (Horsley-Witten, 2011), which were inadequate to control the large amount of sediment mobilized during storms (Horsley-Witten, 2012). During the study period (2012-2014), additional sediment controls were installed and large piles of overburden were overgrown by vegetation (Figure 2). In late 2014, after the monitoring reported here, large retention ponds were installed to capture sediment runoff. See Holst-Rice et al. (2015) for description of sediment mitigation at the quarry.

<Figure 2 here please>

Three water impoundment structures were built in the early 1900's in the Upper watershed for drinking water supply and hydropower, but none are in use and the reservoir at FG1 is filled with sediment. We assume the other reservoirs are similarly filled with coarse sediment and are not retaining fine suspended sediment. A full description is in Appendix A.

3. Methods

The field methods to measure precipitation (P), discharge (Q), and suspended sediment concentration (SSC) to calculate event-wise suspended sediment yield (SSY_{EV}) are described in section 3.1. The equations and analytical methods used to accomplish Objectives 1-3 are described in sections 3.2-3.4.

We quantified the in-stream suspended sediment budget. Other components of sediment budgets not measured in this study include channel erosion, channel deposition, and floodplain deposition (Walling and Collins, 2008). Sediment storage and remobilization can complicate the interpretation of in-stream loads, and identification of a land use signal. In Faga'alu, the channel bed is predominantly large volcanic cobbles and gravel, with no significant deposits of fine sediment. Upstream of the village, the valley is very narrow with no floodplain. In the Lower watershed the channel has been stabilized with cobble reinforced by fencing, so overbank flows

and sediment deposition on the floodplain are not observed. We therefore assume that channel erosion and channel and floodplain deposition are insignificant components of the sediment budget, and the measured sediment yields at the three locations reflect differences in hillslope sediment supply.

SSY_{EV} at FG1-3 was calculated from data on Q, from stage data and stage-Q relationships, and SSC was measured directly or modeled from T data and T-SSC relationships. Storm events were identified from the hydrographs at FG1 and FG3. SSY_{EV} contributions from subwatersheds were calculated by subtracting the contribution of the upstream subwatershed. Anthropogenic disturbance was assessed using estimates of SSY from disturbed portions of the watershed and the Disturbance Ratio (DR). Empirical, log-linear models were developed to predict SSY_{EV} from storm metrics for the undisturbed (“Upper”) and disturbed watersheds (“Total”). Annual SSY was estimated from these models and the ratio of annual storm precipitation to the precipitation during storms where SSY_{EV} was measured.

3.1. Field Data Collection

Data on P, Q, SSC, and T were collected during four field campaigns: January-March 2012, February-July 2013, January-March 2014, and October-December 2014, and several intervening periods of unattended monitoring by instruments with data loggers. Field sampling campaigns were scheduled to coincide with the period of most frequent storms in the November-May wet season, though large storms were sampled throughout the year.

3.1.1. Precipitation (P)

From January, 2012, to December, 2014, P was measured in Faga'alu watershed using two Rainwise RAINEW tipping-bucket rain gages (RG1 and RG2; 20cm dia., 1 min resolution) and a Vantage Pro Weather Station (Wx; 20cm dia. 15 min resolution) (Figure 1). Data at RG2

was only recorded January-March, 2012 to determine an orographic precipitation relationship. Total event precipitation (Psum) was calculated using 1 min interval data from RG1, with data gaps filled by 15 minute interval precipitation data from Wx, and event Erosivity Index (EI) was calculate following the methodology of Kinnell (2013) using only 1 min interval data at RG1.

3.1.2. Water Discharge (Q)

Stream gaging sites were chosen to take advantage of an existing control structure (FG1) and a stabilized stream cross section (FG3) (Duvert et al, 2010). At FG1 and FG3, Q was calculated from stream stage recorded at 15 minute intervals using HOBO and Solinst pressure transducers (PT) and a stage-Q rating curve calibrated to Q measurements. Q was measured manually in the field over a range of flow conditions by the area-velocity method (AV) using a Marsh-McBirney flowmeter (Harrelson et al., 1994; Turnipseed and Sauer, 2010). Q measurements were not made at the highest stages recorded by the PTs, so the stage-Q rating at FG3 was extrapolated using Manning's equation, calibrating Manning's n (0.067) to the Q measurements. At FG1, the flow control structure is a masonry spillway crest of a defunct stream capture, and did not meet the assumptions for using Manning's equation. At FG1, the HEC-RAS model was used to create the stage-Q relationship (Brunner, 2010). See Appendix B for further details stream gaging at FG1 and FG3.

A suitable site for stream gaging was not present at the outlet of the Lower_Quarry subwatershed (FG2), so water discharge at FG2 was calculated as the product of the specific water discharge from FG1 ($\text{m}^3/0.9 \text{ km}^2$) and the watershed area draining to FG2 (1.17 km^2). The specific water discharge at FG2 is assumed to be the same as above FG1 since average slopes, vegetation, and soils of the watersheds are extremely similar. Discharge may be higher from the quarry surface, which represents 5.7% of the Lower_Quarry subwatershed, so Q and SSY at FG2

are conservative, lower-bound estimates, particularly during small events when specific discharge from the Upper watershed was small relative to specific discharge from the quarry. The quarry surface is continually being disturbed, sometimes with large pits excavated and refilled in the course of weeks, as well as intentional water control structures implemented over time. Given the changes in the contributing area of the quarry, estimates of water yield from the quarry were uncertain, so we assumed a uniform specific discharge for the whole Lower_Quarry subwatershed.

3.1.3. Suspended Sediment Concentration (SSC)

SSC was estimated at 15 minute intervals from either 1) linear interpolation of SSC water samples, or 2) turbidity data (T) recorded at 15 minute intervals and a T-SSC relationship calibrated to stream water samples. Stream water samples were collected by grab sampling with 500 mL HDPE bottles at FG1, FG2, and FG3. At FG2, water samples were also collected at 30 min intervals during storm events by an ISCO 3700 Autosampler triggered by a water level sensor. The Autosampler inlet tubing was oriented down-stream, just below the water level sensor, approximately 30 cm above the stream bed, on rebar positioned midstream. Samples were analyzed for SSC on-island using gravimetric methods (Gray, 2014; Gray et al., 2000). Water samples were vacuum filtered on pre-weighed 47mm diameter, 0.7 um Millipore AP40 glass fiber filters, oven dried at 100 C for one hour, cooled and weighed to determine SSC (mg/L).

Interpolation of SSC from grab samples was performed if at least three samples were collected during a storm (Nearing et al., 2007), and if an SSC sample was collected within 30 minutes of peak Q. SSC was assumed to be zero at the beginning and end of each storm if no sample was available for those times (Lewis et al., 2001).

T was measured at FG1 and FG3 using three types of turbidimeters: 1) Greenspan TS3000 (TS), 2) YSI 600OMS with 6136 turbidity probe (YSI), and 3) Campbell Scientific OBS500 (OBS). All turbidimeters were permanently installed in PVC housings near the streambed with the turbidity probe submerged at all flows and oriented downstream. Despite regular maintenance, debris fouling and data loss during storm and baseflows occurred many times.

The T-SSC relationship can be unique to each region, stream, instrument or even each storm event (Lewis et al., 2001), and can be influenced by water color, dissolved solids, organic matter, temperature, and particle shape, size, and composition. However, T has proved to be a robust surrogate measure of SSC in streams (Gippel, 1995), and is most accurate when a unique T-SSC relationship is developed for each instrument separately, using in situ SSC samples during storms (Lewis, 1996; Minella et al., 2008). A unique, linear T-SSC relationship was developed for each turbidimeter, at each location, using T data and SSC samples from storm periods only (r^2 values 0.79-0.99). See Appendix D for details on the T-SSC relationships. The T-SSC relationships are critical to this analysis, so the cumulative error or uncertainty (root mean square error and % error) from these relationships were combined with other error sources to estimate uncertainty in the SSY_{EV} estimates in the following section.

3.1.4. Cumulative Probable Error (PE)

Uncertainty arises from errors in measured and modeled water discharge and sediment concentration data used to calculate SSY_{EV} (Harmel et al., 2006). The Root Mean Square Error (RMSE) method estimates the "most probable value" of the cumulative or combined error by propagating the error from each measurement and modeling procedure, i.e. stage-Q and T-SSC,

to the final SSY_{EV} calculation (Topping, 1972). The resulting cumulative probable error (PE) is the square root of the sum of the squares of the maximum values of the separate errors:

$$PE = \sqrt{(E_{Qmeas}^2 + E_{SSCmeas}^2) + (E_{Qmod}^2 + E_{SSCmod}^2)} \quad \text{Equation 2}$$

where PE is the cumulative probable error for SSY_{EV} estimates ($\pm\%$), E_{Qmeas} is uncertainty in Q measurements ($\pm\%$), $E_{SSCmeas}$ is uncertainty in SSC measurements ($\pm\%$), E_{Qmod} is uncertainty in the Stage-Q relationship (RMSE, as $\pm\%$ of the mean observed Q), E_{SSCmod} is uncertainty in the T-SSC relationship or from interpolating SSC samples (RMSE, as $\pm\%$ of the mean observed SSC) (Harmel et al., 2009).

E_{Qmeas} and $E_{SSCmeas}$ were taken from the DUET-H/WQ software tool lookup tables (Harmel et al., 2009). The effect of uncertain SSY_{EV} estimates may complicate conclusions about anthropogenic impacts and SSY_{EV} -Storm Metric relationships, but difference in SSY from undisturbed and disturbed areas was expected to be much larger than the cumulative uncertainty. High uncertainty is common in sediment yield studies where successful models estimate SSY with ± 50 -100% accuracy (Duvert et al., 2012). PE was calculated for SSY_{EV} from the Upper and Total watersheds, but not for the Lower subwatershed since it was calculated as the difference of SSY_{EV_UPPER} and SSY_{EV_TOTAL} .

3.2 Compare SSY_{EV} for disturbed and undisturbed watersheds

3.2.1. Suspended Sediment Yield during storm events (SSY_{EV})

SSY_{EV} was sampled at the outlets of three subwatersheds with different land covers, undisturbed forest (FG1), the quarry (FG2), and the village (FG3), by integrating continuous estimates of SSY , calculated from measured or modeled Q and measured or modeled SSC (Duvert et al., 2012):

$$SSY_{EV} = k \int_{t=0}^T Q(t) * SSC(t) * dt \quad \text{Equation 1}$$

where SSY_{EV} is suspended sediment yield (tons) for an event from $t=0$ at storm start to T =storm end, SSC is suspended sediment concentration (mg/L), and Q is water discharge (L/sec), and k converts from mg to tons (10^{-9}).

SSY_{EV} from subwatersheds was calculated as follows: SSY_{EV} from the Upper subwatershed, draining undisturbed forest, was sampled at FG1; SSY_{EV} from the Lower_Quarry subwatershed, draining undisturbed forest and the quarry between FG1 and FG2, was calculated as the difference between SSY_{EV} measured at FG1 and FG2; SSY_{EV} from the Lower_Village subwatershed, which drains undisturbed forest and the village between FG2 and FG3, was calculated as the difference between SSY_{EV} measured at FG2 and FG3; the Lower subwatershed, which drains undisturbed forest, the quarry, and village between FG1 and FG3, was calculated as the difference between SSY_{EV} measured at FG1 and FG3. SSY_{EV} from the Total watershed was measured at FG3 (Figure 1; Table 1).

Storm events can be defined by precipitation (Hicks, 1990) or discharge data (Duvert et al., 2012), and the method used to identify storm events can significantly influence the analysis of SSY_{EV} (Gellis, 2013). Due to the high number of storm events and the prevalence of complex storm events observed at the study site, we used a digital filter signal processing technique (Nathan and McMahon, 1990) in the R-statistical package EcoHydRology (Fuka et al., 2014). Spurious events were sometimes identified due to instrument noise, so only events with quickflow for at least one hour and peak flow greater than 110% of baseflow were included (See Appendix C for example).

3.2.2. SSY from disturbed and undisturbed portions of subwatersheds

Land cover in the Lower subwatersheds (Lower_Quarry and Lower_Village) includes both undisturbed and human-disturbed surfaces (Table 1). SSY_{EV} from disturbed areas was estimated:

$$SSY_{EV_distrb} = SSY_{EV_subws} - (sSSY_{EV_UPPER} * Area_{undist}) \quad \text{Equation 3}$$

where SSY_{EV_distrb} is SSY_{EV} from disturbed areas only (tons), SSY_{EV_subws} is SSY_{EV} (tons) measured from the subwatershed (e.g. SSY_{EV_FG3}- SSY_{EV_FG2}), $sSSY_{EV_UPPER}$ is specific SSY_{EV} (tons/km²) from the Upper subwatershed (SSY_{EV_FG1}), and $Area_{undist}$ is the area of undisturbed forest in the subwatershed (km²).

The disturbance ratio (DR) is the ratio of SSY_{EV} under current conditions to SSY_{EV} under pre-disturbance conditions:

$$DR = \frac{SSY_{EV_subw}}{A_{subw} * sSSY_{EV_UPPER}} \quad \text{Equation 4}$$

where A_{subw} is the area of the subwatershed.

Both Equations 3 and 4 assume that $sSSY_{EV}$ from forested areas in the Lower subwatershed equals $sSSY_{EV}$ from the undisturbed Upper watershed and that pre-disturbance land cover was forested throughout the watershed.

3.3 Modeling SSY_{EV} with storm metrics

The relationship between SSY_{EV} and storm metrics was modelled as a log-linear function:

$$SSY_{EV} = \alpha X^{\beta} \quad \text{Equation 5}$$

where X is a storm metric, and the regression coefficients α and β are obtained by ordinary least squares regression on the logarithms of SSY_{EV} and X (Basher et al., 2011; Duvert et al., 2012; Hicks, 1990). Model fits for each storm metric were compared using coefficients of determination (r^2) and Root Mean Square Error (RMSE). The correlation between storm metrics (X) and SSY_{EV} were quantified using both parametric (Pearson) and non-parametric (Spearman) correlation coefficients.

Four storm metrics were tested as predictors of SSY_{EV} : Total event precipitation (Psum), event Erosivity Index (EI) (Hicks, 1990; Kinnell, 2013), Total event water discharge (Qsum), and maximum event water discharge (Qmax) (Duvert et al., 2012; Rodrigues et al., 2013). The Erosivity Index describes the erosive power of rainfall (Kinnell, 2013). SSY_{EV} and the discharge metrics (Qsum and Qmax) were normalized by watershed area to compare different sized subwatersheds.

The regression coefficients (α and β) for the Upper and Total watersheds were tested for statistically significant differences using Analysis of Covariance (ANCOVA) (Lewis et al., 2001). A higher intercept (α) for the human-disturbed compared to the undisturbed watershed indicates higher sediment yield for the same size storm event. A difference in slope (β) indicates the relative subwatershed contributions vary with storm size.

3.4. Estimation of annual SSY

Annual SSY and sSSY were estimated using 1) the developed storm metric-SSY models, and 2) the ratio of annual storm precipitation to precipitation measured during storms with SSY_{EV} data.

An annual SSY time-series was not possible due to the discontinuous field campaigns and failure of or damage to the instruments. Continuous records of P and Q were available for 2014, so the storm metric-SSY_{EV} models (Equation 5) were used to predict SSY_{EV} for all storms in 2014 (Basher et al., 1997). For storms missing Q_{max} data at FG3, Q_{max} was predicted from a linear regression between Q_{max} at FG1 and Q_{max} at FG3 for the study period ($R^2 = 0.88$).

Annual SSY and sSSY were also estimated by multiplying SSY_{EV} from measured storms by the ratio of annual storm precipitation ($P_{EV_{ann}}$) to precipitation during storms where SSY_{EV} was measured ($P_{EV_{meas}}$):

$$SSY_{ann} = SSY_{EV_{meas}} * \frac{P_{EV_{ann}}}{P_{EV_{meas}}} \quad \text{Equation 6}$$

where SSY_{ann} is estimated annual SSY from storms, $SSY_{EV_{meas}}$ is SSY_{EV} from sampled storms (all, Tables 2 and 4), $P_{EV_{meas}}$ is precipitation during the sampled storms, and $P_{EV_{ann}}$ is the precipitation during all storm events. Equation 6 assumes that the sediment yield per mm of storm precipitation is constant over the year, and insensitive to the size distribution of storms, though there is some evidence that SSY_{EV} increases exponentially with storm size (Lewis et al., 2001; Rankl, 2004). Equation 6 also ignores sediment yield during non-storm periods, which is justified by the low SSC (typically under 20 mg/L) and Q (baseflow) observed between storms.

4. Results

4.1 Field Data Collection

4.1.1 Precipitation

At RG1, P was 3,502 mm, 3,529 mm, and 3,709 mm in 2012, 2013, and 2014, respectively, which averages 94% of long-term P (=3,800 mm) (PRISM data; Craig, 2009). Linear relationships between daily P at RG1 and Wx (slope=0.95, $r^2=0.87$) and RG1 and RG2 (slope=0.75, $r^2=0.85$) were observed. Higher P was expected at higher elevation at RG2 so lower P at RG2 was assumed to be caused by measurement error, as the only available sampling location was a clearing with high surrounding canopy. P data measured at higher elevations would be useful to determine the orographic effect, but for this analysis the absolute values of P in each subwatershed are not important since P and the Erosivity Index are only used as predictive storm metrics. Given the near 1:1 relationship between daily P measured at RG1 and Wx, P was assumed to be homogenous over the watershed.

4.1.2 Water Discharge (Q)

Q at FG1 and FG3 was characterized by low but perennial baseflow, punctuated by flashy hydrograph peaks (Figure 3). Though Q data was discontinuous, observed storm events were generally smaller and more frequent in the October-April wet season compared to the May-September dry season, when the largest event in the three year monitoring period was observed (August 2014).

< Figure 3 here please >

4.1.3 Suspended sediment concentrations (SSC) during storm and non-storm periods

<Figure 4 here please>

An example of a storm event from 2/14/2014 (Figure 4) shows that SSC was highest at FG2 on the rising limb of the hydrograph, and that T and SSC at FG3 were always higher than at FG1. SSC was consistently lowest downstream of the forested watershed (FG1), highest downstream of the quarry (FG2), and intermediate downstream of the village (FG3), during both storm and non-storm periods (Figure 5a, 5b). Mean (μ) and maximum SSC of all storm and non-storm samples were lowest at FG1 ($\mu=28$ mg/L, max=500 mg/L, n=59), highest at FG2 ($\mu=337$ mg/L, max=12,600 mg/L, n=90 grab samples, n=198 from the Autosampler), and intermediate at FG3 ($\mu=148$ mg/L, max=3,500 mg/L, n=159). SSC data at FG1, FG2 and FG3 were highly non-normal, so non-parametric significance tests were applied. SSC was significantly different among the three sites during non-storms and storms ($p<10^{-4}$). Pair-wise Mann-Whitney tests between FG1 and FG2 were significant ($p<10^{-4}$ for both storms and non-storms), but FG2 and FG3 were significantly different for non-storm periods ($p<0.05$) but not for storms ($p>0.10$).
<Figure 5 here please>

SSC varied by several orders of magnitude for a given Q at FG1, FG2, and FG3 due to significant hysteresis observed during storm periods (Figure 4, 6). Maximum SSC at FG1 (500 mg/L) was sampled on 04/23/2013 at high Q ($Q_{FG1}=3,724$ L/sec) (Figure 6a). Maximum SSC at FG2 (12,600 mg/L) and FG3 (3,500 mg/L) were sampled during the same storm (03/05/2012) when brief but intense P caused high SSC runoff from the quarry, but low Q (Figure 6b-c). SSC was diluted downstream of the quarry by the addition of lower SSC runoff from the village and forest draining to FG3.

<Figure 6 here please>

4.1.4 Cumulative Probable Error (PE)

Cumulative Probable Errors (PE) in SSY_{EV} , calculated from measurement and model errors in Q and SSC data, were 28-49% ($\mu=43\%$) at FG1 and 36-118% ($\mu=94\%$) at FG3.

The measurement error for Q at FG1 and FG3 was 8%, including area-velocity measurements (6%), continuous Q measurement in a natural channel (6%), pressure transducer error (0.1%), and streambed condition (firm, stable bed=0%) (DUET-H/WQ look-up table (Harmel et al., 2006)). Model errors were 32% for the stage-Q rating curve using Manning's equation at FG3, and 22% using HEC-RAS at FG1.

The measurement error for SSC was 16 %, including interpolating over a 30 min interval (5%), sampling during stormflows (3%), and measuring SSC by filtration (3.9%) (DUET-H/WQ look-up table (Harmel et al., 2006)). Model errors of the T-SSC relationships were 16% (4 mg/L) for the YSI and TS turbidimeters at FG1, 113% (348 mg/L) for the YSI turbidimeter at FG3, and 46% (48 mg/L) for the OBS turbidimeter at FG3.

4.2 Compare SSY_{EV} for disturbed and undisturbed watersheds

A total of 210 storms were identified January, 2012, to December, 2014. A total of 169 storms had simultaneous Q data at FG1 and FG3 (Appendix C, Table 1). SSC data from T or interpolated grab samples were recorded during 112 (FG1) and 74 storms (FG3). Of those storms, 42 had simultaneous P, Q, and SSC data at FG1 and FG3. SSC data were collected at FG2 for 8 storms to calculate SSY_{EV} from the Lower_Quarry and Lower_Village subwatersheds separately. Storm events ranged from 1 hour to 2 days, with mean duration of 13 hours.

4.2.1. Suspended sediment yield during storm events (SSY_{EV}) from Upper, Lower, and Total watersheds

For the 42 storms with P, Q, and SSC data at both FG1 and FG3, SSY_{EV_Total} was 129 ± 121 tons, with 17 ± 7 tons from the Upper watershed and 112 tons from the Lower subwatershed (Table 2). The Upper and Lower subwatersheds are similar in size (0.90 km^2 and 0.88 km^2) but SSY_{EV_Lower} accounted for 87% of SSY_{EV} at the watershed outlet. The DR (Equation 4, $sSSY_{EV_Upper} = 18.8 \text{ tons/km}^2$) suggests $sSSY_{EV}$ has increased by 6.8x in the Lower subwatershed, and 3.9x for the Total watershed compared with undisturbed forest in the Upper watershed.

<Table 2 here please>

4.2.2 SSY from disturbed and undisturbed portions of Upper, Lower, and Total watersheds

In the Lower subwatershed, disturbed areas cover 10% of the surface but contributed 87% of SSY_{EV_Lower} . In the Total watershed, disturbed areas cover only 5.2% of the surface but contributed 75% of SSY_{EV_Total} . $sSSY$ from disturbed areas in the Lower subwatershed was $1,095 \text{ tons/km}^2$, or 58x the $sSSY$ of undisturbed forest (Table 3).

<Table 3 here please>

4.2.3. Suspended sediment yield during storm events (SSY_{EV}) from Lower_Quarry and Lower_Village watersheds

For the 8 storms with P, Q, and SSC data at FG1-3, $sSSY$ from the Upper, Lower_Quarry, Lower_Village, and the Total watershed was 15, 61, 27, and 26 tons/km^2 , respectively, with 29% of SSY_{EV} from the Upper subwatershed, 36% from the Lower_Quarry subwatershed, and 35% from the Lower_Village subwatershed. The storms in Table 4 may

underrepresent the contributions of the quarry and village to SSY, since they show a smaller increase in SSY from the Total watershed ($1.7 \times \text{SSY}_{\text{Upper}}$) compared with the 42 storms in Table 2 ($3.9 \times \text{SSY}_{\text{Upper}}$). sSSY increased by $4.1 \times$ in the Lower_Quarry subwatershed and $1.8 \times$ in the Lower_Village subwatershed compared with the undisturbed Upper watershed.

<Table 4 here please>

4.2.4 SSY from disturbed and undisturbed portions of *Lower_Quarry* and *Lower_Village* watersheds

Disturbed areas cover small fractions of the subwatersheds, yet contributed roughly 77% of $\text{SSY}_{\text{EV_LOWER_QUARRY}}$ (6.5% disturbed) and 51% of $\text{SSY}_{\text{EV_LOWER_VILLAGE}}$ (11.7% disturbed). Similarly, disturbed areas cover 5.2% of the Total watershed but contributed 75-45% of $\text{SSY}_{\text{EV_TOTAL}}$ (Tables 3 and 5). sSSY from disturbed areas in the Upper (37 tons/km^2), Lower_Quarry (722 tons/km^2), and Lower_Village subwatersheds (116 tons/km^2) suggested that disturbed areas increase sSSY over forested conditions by $49 \times$ and $8 \times$ in the Lower_Quarry and Lower_Village subwatersheds, respectively. Human disturbance in the Lower_Village subwatershed increased SSY_{EV} above natural levels but the magnitude of disturbance was much lower than the quarry.

<Table 5 here please>

4.3 Modeling SSY_{EV} with storm metrics

4.3.1. *Selecting the best predictor of SSY_{EV}*

Q_{sum} and Q_{max} were the best predictors of SSY_{EV} for the forested Upper watershed, and P_{sum} and Q_{max} were the best predictors for the Total watershed (Figure 7, Table 6). SSY_{EV} is calculated from Q so it is expected that Q_{sum} correlated closely with SSY_{EV} (Duvert et al., 2012; Rankl, 2004). Discharge metrics were highly correlated with SSY_{EV} in the Total watershed,

suggesting they are good predictors in both disturbed and undisturbed watersheds. Most of the scatter in the Q_{max} - SSY_{EV} relationship is observed for small events, and Q_{max} correlated strongly with the largest SSY_{EV} values, when most of the annual SSY is generated (Table 6).

<Table 6 here please>

P was measured near the quarry (RG1), which may reflect precipitation characteristics more accurately in the Lower than the Upper watershed, and account for the lower correlation coefficients between SSY_{EV_UPPER} and P_{sum} and EI . SSY_{LOWER} was hypothesized to be generated by sheetwash and rill formation at the quarry and agricultural plots, whereas SSY_{UPPER} was hypothesized to be from channel processes and mass wasting. Mass wasting can contribute large pulses of sediment which can be deposited near or in the streams and entrained at high discharges during later storm events. Given the high correlation coefficients between SSY_{EV} and Q_{max} in both watersheds, Q_{max} may be a promising predictor that integrates both precipitation and discharge processes.

4.3.2. Effect of event size and watershed disturbance

SSY_{EV_TOTAL} was higher than SSY_{EV_UPPER} for the full range of measured storms with the exception of a few events. The outlier events could be from measurement error or mass movements in the Upper watershed. The separation of multi-peak storm events, storm sequence, and antecedent conditions may also play a role. While strong seasonality is not observed in Faga'alū, low rainfall can persist for several weeks, perhaps altering water and sediment dynamics in subsequent storm events.

All storm metric- SSY_{EV} model intercepts (α) were significantly different ($p < 0.01$), but only the Q_{sum} - SSY_{EV} model showed significantly different slopes (β , $p < 0.01$) (Figure 7, Table 6). The Q_{sum} - SSY_{EV} models indicate that SSY_{EV} from the Upper and Total watersheds converge

at higher Q_{sum} values. Conversely, the P_{sum} - and Q_{max} - SSY_{EV} models show no change in relative contributions of SSY over the range of storm sizes (Figure 7).

<Figure 7 here please>

The relative sediment contribution from the human-disturbed watershed was hypothesized to diminish with increasing storm size, but the results from P and Q metrics were contradictory. The Q_{sum} - SSY_{EV} model shows a decrease in relative contribution, but the P_{sum} - and Q_{max} - SSY_{EV} models show no change over increasing storm size (Figure 7). It was hypothesized that SSY_{EV} from undisturbed forest would become the dominant source for larger storms, but the DR remains high for large storms due to naturally low SSY_{EV} from forest areas in Faga'alu watershed. This suggests that disturbed areas were not supply limited for the range of sampled storms.

4.4 Estimation of annual SSY

Annual $sSSY$ estimates depended on which storm metric or set of storms (all, Table 2, Table 4) was used. Overall, the Q_{max} model and Equation 6 using all events gave similar annual SSY estimates at both the Upper watershed (41-61 tons/yr) and the Total watershed (428-439 tons/yr). The P_{sum} model resulted in much lower estimates due to higher scatter about the P_{sum} - SSY_{EV} relationship for large events, compared with the more robust Q_{max} - SSY_{EV} model (Table 7).

<Table 7 here please>

Annual storm precipitation ($P_{EV_{ann}}$) in 2014 was 2,770 mm, representing 69% of total annual precipitation (3,709 mm). The remaining 31% of precipitation did not result in a rise in stream level sufficient to be classified as an event with the method used here. All storms with measured SSY_{EV_UPPER} from 2012-2014 included 3,457 mm of precipitation ($P_{EV_{meas}}$), or 125%

of P_{EVann} , so estimated annual SSY_{UPPER} (Equation 6) was 41 tons/yr (45 tons/km²/yr). All storms with measured SSY_{EV_TOTAL} from 2012-2014 included 2,628 mm of precipitation, or 95% of expected annual storm precipitation so estimated annual SSY_{TOTAL} was 428 tons/yr (241 tons/km²/yr).

5. Discussion

5.1 Compare SSC and SSY_{EV} for disturbed and undisturbed watersheds

5.1.1 Compare SSC for disturbed and undisturbed watersheds in Faga'alu

At FG1, SSC variability during storms was assumed to be caused by landslides or channel erosion (including previous landslides) (Figure 6). Anecdotal and field observations reported unusually high SSC at FG1 during 2013, possibly from landsliding during previous large storms (G. Poysky, pers. comm.). At FG2 and FG3, additional variability in the Q-SSC relationship was caused by changing sediment availability from quarrying operations and construction in the village. High SSC values observed downstream of the quarry (FG2) during low Q were caused by two mechanisms: 1) P that generated high SSC runoff but did not result in storms identified on the hydrograph, and 2) washing fine sediment into the stream during quarry operations.

Given the close proximity of the quarry to the stream, SSC at FG2 was highly influenced by mining activity like rock extraction, crushing, and/or hauling operations. During 2012, a common practice for removing fine sediment from crushed aggregate was to rinse it with water pumped from the stream. In the absence of retention structures the fine sediment was discharged directly to Faga'alu stream, causing high SSC during non-storm periods with no P in the preceding 24 hours (solid symbols, Figure 6b-c). In 2013 and 2014, riverine discharge or rinsed

sediment was discontinued, and sediment was piled on-site where severe erosion of these changing stockpiles caused high SSC only during storm events.

5.1.2 Compare SSY_{EV} with other kinds of sediment disturbance

SSY at Faga’alu was increased by 3.9x compared with the natural background. Studies in similar watersheds have documented one to several orders of magnitude increases in SSY from land use that disturbs a small fraction of the watershed area (Stock et al., 2010). Urbanization (construction-phase) and mining can increase sediment yield by two to three orders of magnitudes in catchments of several km², exceeding yields from the most unstable, tectonically active natural environments of Southeast Asia (Douglas, 1996). In Kawela watershed on Molokai, less than 5% of the land produces most of the sediment, and only 1% produces ~50% of the sediment (Risk, 2014; Stock et al., 2010). In three basins on St. John, US Virgin Islands unpaved roads increased sediment delivery rates by 3-9 times (Ramos-Scharrón and Macdonald, 2005).

Disturbances at larger scales in other coral reef areas have been similar to Faga’alu, such as the the Great Barrier Reef (GBR) catchment (423,000 km²) where SSY increased by a factor of 5.5x (Kroon et al., 2012) since European settlement.. Mining has been a major contributor of sediment in other watersheds on volcanic islands with steep topography and high precipitation, increasing sediment yields by 5-10 times in a watershed in Papua New Guinea (Hettler et al., 1997; Thomas et al., 2003). In contrast to other land disturbances like fire, logging, or urbanization where sediment disturbance decreases over time, the disturbance from mining is persistently high. Disturbance magnitudes are similar to the construction phase of urbanization (Wolman and Schick, 1967), or high-traffic unpaved roads (Reid and Dunne, 1984), but persist or even increase over time.

While unpaved roads are often a major sediment source in humid forested regions (Lewis et al., 2001; Ramos-Scharrón and Macdonald, 2005; Reid and Dunne, 1984), field observations at Faga’alu suggested that most roads in the urban area were stabilized with aggregate and not generating significant amounts of sediment. Other disturbances in Faga’alu included a few small agricultural plots, small construction sites and bare dirt on roadsides. Repeated surface disturbance at the quarry is a key process maintaining high rates of sediment generation. Given the large distance to other sources of building material, aggregate mining and associated sediment disturbance may be a critical sediment source on remote islands in the Pacific and elsewhere.

Annual sSSY from the quarry was estimated from Equation 6 to be approximately 2,800 tons/km²/yr. The quarry surfaces are comprised of haul roads, piles of overburden, and steep rock faces which can be described as a mix of unpaved roads and cut-slopes. sSSY from cutslopes varies from 0.01 tons/km²/yr in Idaho (Megahan, 1980) to 105,000 tons/km²/yr in Papua New Guinea (Blong and Humphreys, 1982), so the sSSY ranges measured in this study are well within the ranges found in the literature.

5.2 Modeling SSY_{EV} with storm metrics

The anthropogenic impact on SSY_{EV} may vary by storm magnitude, as documented in Pacific Northwest forests (Lewis et al., 2001). As storm magnitude increases, water yield and/or SSY_{EV} from natural areas may increase relative to human-disturbed areas, diminishing anthropogenic impact relative to the natural baseline. While large storms account for most SSY under undisturbed conditions, the disturbance ratio (DR) may be highest for small storms, when background SSY_{EV} from the undisturbed forest is low and erodible sediment from disturbed surfaces is the dominant source (Lewis et al., 2001). For large storms, mass movements and bank

erosion in undisturbed areas can increase the natural background and reduce the DR for large events.

The Q-SSC relationship (sediment rating curve) coefficients have no physical meaning, but the intercept (α) and slope (β) can be interpreted as a function of watershed characteristics (Asselman, 2000). Similarly, Rankl (2004) hypothesized that the intercept in the Q_{\max} - SSY_{EV} relationship varied with the watershed's sediment availability and erodibility. While slopes in log-log space can be compared directly (Duvert et al., 2012), intercepts must be plotted in similar units and normalized by watershed area. In five semi-arid to arid watersheds (2.1 - 1,538 km²) in Wyoming, United States, SSY_{EV} - Q_{\max} relationship intercepts ranged from 111 - 4,320 (Q_{\max} in m³/s/km², SSY_{EV} in Mg/km²) (Rankl, 2004). In eight sub-humid to semi-arid watersheds (0.45-22 km²), intercepts ranged from 25 - 5,039 (Duvert et al., 2012). In Faga'alu, intercepts were 0.35 and 1.38 in the undisturbed and disturbed watersheds, respectively. These intercepts are 1-2 orders of magnitude lower than in Rankl (2004) and Duvert et al. (2012), suggesting that sediment availability is relatively low in natural and human-disturbed conditions in Faga'alu, likely due to the dense forest cover.

High slope values in the log-log plots (β coefficient) suggest that small increases in stream discharge correlate with large increases in sediment load due to the erosive power of the stream or the availability of new sediment sources at high Q (Asselman, 2000). Rankl (2004) assumed that the slope was a function of rainfall intensity on hillslopes and found that the slopes were not statistically different among watersheds and ranged from 1.07-1.29 in semi-arid Wyoming. In watersheds in Duvert et al. (2012), slopes ranged from 0.95-1.82, and from 1.06-2.45 in eighteen other watersheds (0.60-1,538 km²) in diverse geographical settings (Basher et al., 1997; Fahey and Marden, 2000; Hicks et al., 2009; Rankl, 2004; Tropeano, 1991). In

Faga'alu, slopes were 1.51 and 1.40 in the undisturbed and disturbed watersheds, respectively. These slopes are consistent with the slopes in Rankl (2004) and Duvert et al. (2012), despite large differences in climate and land cover.

In Faga'alu, SSY_{EV} was least correlated with the EI. Rodrigues et al. (2013) hypothesized that EI is poorly correlated with SSY_{EV} due to the effect of previous events on antecedent moisture conditions and in-channel sediment storage. Cox et al. (2006) found EI was more correlated with soil loss in an agricultural watershed than a forested watershed, and Faga'alu is mainly covered in dense forest. Similar to other studies, the highest correlations with SSY_{EV} at Faga'alu were observed for discharge metrics Q_{sum} and Q_{max} (Basher et al., 2011; Duvert et al., 2012; Fahey et al., 2003; Hicks, 1990; Rankl, 2004; Rodrigues et al., 2013). While Q_{sum} and P_{sum} had higher correlations in one watershed, Q_{max} was a good predictor of SSY_{EV} in both the disturbed and undisturbed watersheds.

5.3 Estimation of annual SSY: comparison with other tropical islands

Sediment yield is highly variable among watersheds, but is generally controlled by climate, vegetation cover, and geology, with human disturbance playing an increasing role in the 20th century (Syvitski et al., 2005). Sediment yields in tropical Southeast Asia and high-standing islands between Asia and Australia range from ~ 10 tons/km²/yr in the granitic Malaysian Peninsula to $\sim 10,000$ tons/km²/yr in the tectonically active, steeply sloped island of Papua New Guinea (Douglas, 1996). Sediment yields from Faga'alu are on the lower end of the range, with sSSY of 45-68 tons/km²/yr from the undisturbed Upper watershed, and 241-247 tons/km²/yr from the disturbed Total watershed.

Milliman and Syvitski (1992) report high average sSSY (1,000-3,000 tons/km²/yr) from watersheds (10-100,000 km²) in tropical Asia and Oceania, though their regional models of sSSY

as a function of basin size and maximum elevation predict only 13 tons/km²/yr from watersheds with peak elevation 500-1,000 m (highest point of Upper Faga'alu subwatershed is 653 m), and 68 tons/km²/yr for max elevations of 1,000-3,000. Given the high vegetation cover and lack of human disturbance in the Upper subwatershed, sSSY is expected to be lower than watersheds presented in Milliman and Syvitski (1992), but sSSY from the forested Upper Faga'alu subwatershed (45-68 tons/km²/yr) was approximately three to five times higher than the prediction from the Milliman and Syvitski (1992) model (13 tons/km²/yr). There is large scatter around their model for smaller watersheds, and the Faga'alu data fall within the range of scatter (Figures 5e and 6e in Milliman and Syvitski (1992)). Faga'alu is also a much smaller watershed and the study period was relatively short (3 years) compared to others included in their models.

Sediment yield was measured from two Hawaiian watersheds which are physiographically similar though much larger than Faga'alu,: Hanalei watershed on Kauai ("Hanalei", 54 km²), and Kawela watershed on Molokai ("Kawela", 14 km²) (Table 8) (Ferrier et al., 2013; Stock and Tribble, 2010). Hanalei had slightly higher rainfall (3,866 mm/yr) than Faga'alu (3,247 mm/yr) but slightly lower SSC (mean 63 mg/L, maximum of 2,750 mg/L) than the Total Faga'alu watershed (mean 148 mg/L, maximum 3,500 mg/L) (Ferrier et al., 2013; Stock and Tribble, 2010). Kawela is drier than Faga'alu (P varies with elevation from 500-3,000 mm) and had much higher SSC (mean 3,490 mg/L, maximum 54,000 mg/L) than the Total Faga'alu watershed. SSY from Hanalei was 369 ± 114 tons/km²/yr (Ferrier et al., 2013), which is higher than the undisturbed subwatershed in Faga'alu (45-68 tons/km²/yr) but similar to the disturbed (430-441 tons/km²/yr) subwatersheds. Stock and Tribble (2010) estimated SSY from Kawela was 459 tons/km²/yr, similar to the disturbed Lower Faga'alu watershed, but nearly twice as high as the Total Faga'alu watershed. Overall, both Hawaiian watersheds have higher

SSY than Faga'alu, which is consistent with the low Q_{max} -SSY_{EV} intercepts and suggests Faga'alu has relatively low erosion rates for a steep, volcanic watershed. Precipitation variability may contribute to the difference in SSY, so a more thorough comparison between Hanalei and Faga'alu would require a storm-wise analysis of the type performed here.

<Table 8 here please>

6. Conclusion

Human disturbance has increased sediment yield to Faga'alu Bay by 3.9x over pre-disturbance levels. The human-disturbed subwatershed accounted for the majority (87%) of Total sediment yield, and the quarry (1.1% of watershed area) contributed about a third of Total SSY to the Bay. Q_{max} was a good predictor of SSY_{EV} in both the disturbed and undisturbed watersheds, making it a promising predictor in diverse environments. The slopes of the Q_{max} -SSY_{EV} relationships were comparable with other studies, but the model intercepts were an order of magnitude lower than intercepts from watersheds in semi-arid to semi-humid climates. This suggests that sediment availability is relatively low in the Faga'alu watershed, either because of the heavy forest cover or volcanic rock type.

This study presents an innovative method to combine sampling and analysis strategies to measure sediment contributions from key sources, estimate baseline annual sediment yields prior to management, and rapidly develop an empirical sediment yield model for a remote, data-poor watershed. While the instantaneous Q-SSC relationship illustrated large increases in SSC downstream of the quarry, the hysteresis and interstorm variability meant that a single Q-SSC relationship could not be used to estimate sediment loading, which is common in many watersheds (Asselman, 2000; Stock and Tribble, 2010). From a management perspective, the event-wise approach was useful for determining change over space and time without the problem

of interannual variability in precipitation or the need for continuous, multi-year monitoring in a remote area. This approach is less expensive than efforts to measure annual yields since it does not require a complete year of monitoring, and can be rapidly conducted if mitigation or disturbance activities are already planned.

Acknowledgements

Funding for this project was provided by NOAA Coral Reef Conservation Program (CRCP) through the American Samoa Coral Reef Advisory Group (CRAG). Kristine Buccianeri at CRAG and Susie Holst at NOAA CRCP provided significant support. Christianera Tuitele, Phil Wiles, and Tim Bodell at American Samoa Environmental Protection Agency (ASEPA), and Fatima Sauafea-Leau and Hideyo Hattori at NOAA, provided on-island coordination with traditional local authorities. Dr. Mike Favazza provided critical logistical assistance in American Samoa. Robert Koch at the American Samoa Coastal Zone Management Program (ASCMP) and Travis Bock at ASEPA assisted in accessing historical geospatial and water quality data. Professor Jameson Newtonson, Rocco Tinitali, and Valentine Vaeoso at American Samoa Community College (ASCC), Meagan Curtis and Domingo Ochavillo at American Samoa Department of Marine and Wildlife Resources (DMWR), Don and Agnes Vargo at American Samoa Land Grant, Christina Hammock at NOAA American Samoa Climate Observatory, and Greg McCormick at San Diego State University supported the field and laboratory work. George Poysky, Jr., George Poysky III, and Mitch Shimisaki at Samoa Maritime Ltd. provided unrestricted access to the Faga'alu quarry, and historical operation information. Faafetai tele lava.

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