# TITLE:

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

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## ABSTRACT

Suspended sediment concentrations (SSC) and yields (SSY) were measured during storm and non-storm periods (2012-2014) from undisturbed and human-disturbed portions of a small (1.8 km²), mountainous watershed that drains to a sediment-stressed coral reef. Event-wise SSY (SSYEV) was calculated for 142 storms from measurements of water discharge (Q), turbidity (T), and SSC measured downstream of three key sediment sources: undisturbed forest, an aggregate quarry, and a village. SSC and SSYEV were significantly higher downstream of the quarry during both storm- and non-storm periods. The human-disturbed subwatershed accounted for an average of 71-87% of SSYEV from the total watershed, and has increased loads to the coast by 3.9x over natural background. Specific SSY (tons/area) from the disturbed quarry area was 49x higher than from natural forest compared with 8x higher from the village. The quarry, which covers 1.1% of the total watershed area, contributed 36% of total SSYEV at the outlet. Similar to mountainous watersheds in semi-arid and temperate climates, SSYEV from both the undisturbed and disturbed watersheds correlated closely with maximum event discharge (Qmax), event total precipitation and event total Q, but not with a precipitation erosivity index. Best estimates of annual sediment loads (yields) varied from 41-61 tons/yr (45-68 tons/km²/yr) from the undisturbed subwatershed, 310-388 tons/yr (350-441 tons/km²/yr) from the human-disturbed subwatershed, and 360-439 tons/yr (200-247 tons/km2/yr) from the total watershed. Sediment yield was very sensitive to disturbance; only 5.2% of the watershed is disturbed by humans but increased sediment yield from the disturbed watershed by 3.9x. While unpaved roads are often identified as a source of sediment in humid forested regions, field observations suggested that most roads in the urban area were paved or stabilized with aggregate. 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. 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 activities including deforestation, agriculture, road construction, 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, including coral reefs that occur near the outlets of impacted watersheds. Sediment impacts coral 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, which have a high potential for erosion due to high rainfall, extreme weather events, steep slopes, and erodible soils. 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 capacity of the watershed to buffer increased hillslope sediment supply (Walling, 1999). Such environments characterize many volcanic islands in the south Pacific where coral reefs are impacted by sediment.

A large proportion of a watershed's sediment yield can originate from disturbed areas that cover a relatively small fraction of the watershed area. Unpaved roads covering 0.3-0.9% of the watershed area were the dominant sediment source in disturbed watersheds on St. John in the Caribbean, and increased sediment yield to the coast by 5-9 times relative to undisturbed watersheds (Ramos-Scharrón and Macdonald, 2007). In the Pacific Northwest of the United States, several studies found most road-generated sediment can originate 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 could generate 130 times as much sediment as abandoned roads (Reid and Dunne, 1984). In a watershed disturbed by grazing on Molokai, Hawaii, less than 5% of the land produces most of the sediment, and only 1% produces approximately 50% of the sediment (Risk, 2014; Stock et al., 2010), suggesting that management should focus on identifying, quantifying, and mediating erosion hotspots.

Sediment management requires linking land use changes and mitigation strategies to changes in sediment yields at the watershed outlet (Walling and Collins, 2008). A sediment budget quantifies sediment as it moves 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 both land use change and erosion management due to high sediment storage capacity on hillslopes and in the channel. Sediment yield from disturbed areas can be large but may not be important compared to naturally high yields from undisturbed areas. While a full description of all sediment production and transport processes are of scientific interest, the sediment budget needs to be simplified to be used as a management tool (Slaymaker, 2003). Most management applications require only that the order of magnitude or the relative importance of process rates be known, so Reid and Dunne (1996) argue a management-focused sediment budget can be developed quickly in situations where the management 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. The limited data has also made it difficult to develop reliable sediment yield models for ungauged watersheds. Existing sediment yield models are often designed for agricultural landscapes and are not well-calibrated to the climatic, topographic, and geologic conditions found on steep, tropical islands. Most readily available models also do not incorporate many of the important processes that generate sediment in steep watersheds, including 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 can also improve regional-scale sediment yield models (Duvert et al., 2012).

Traditional approaches to quantifying human impact on sediment budgets, including comparison of total annual yields (Fahey et al., 2003) and sediment rating curves (Asselman, 2000; Walling, 1977), are complicated by interannual climatic variability and hysteresis in the discharge-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, if an undisturbed watershed is not in a steady-state condition, sediment yields may decrease over time as it reaches equilibrium, or the sediment contributions from different subwatersheds may change with time (Ferrier et al., 2013; Perroy et al., 2012). At decadal scales, cyclical climatic variability like El Nino-Southern Oscillation (ENSO) events or Pacific Decadal Oscillation (PDO) patterns can significantly alter sediment yield from undisturbed watersheds (Wulf et al., 2012).

As an alternative to comparing annual sediment loads, SSY generated by storm events of the same magnitude can be compared to assess the contribution of individual subwatersheds to total SSY (Zimmermann et al., 2012), determine changes in SSY from the same watershed over time (Bonta, 2000), and compare the responses of different watersheds 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 (SSYEV) may correlate with storm metrics such as total precipitation, the Erosivity Index (Kinnell, 2013), or total discharge, but the best correlation has consistently been found with maximum event discharge (Qmax). Several researchers have hypothesized that Qmax integrates the hydrological response of a watershed, making it a good predictor of SSYEV in diverse environments (Duvert et al., 2012; Rankl, 2004). High correlation between SSYEV and Qmax 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 SSYEV may vary by storm magnitude, as documented in Pacific Northwest forests (Lewis et al., 2001). As storm magnitude increases, water yield and/or SSYEV 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, human-disturbed areas may show the largest disturbance, expressed as a percentage increase above the natural background, for smaller storms (Lewis et al., 2001). The disturbance ratio (DR) may be highest for small storms, when background SSYEV from the undisturbed forest is low and erodible sediment from disturbed surfaces is the dominant source. For large storms, mass movements and bank erosion may contribute to naturally high SSYEV from undisturbed watersheds, increasing the background and reducing 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: Objective 1) Quantify suspended sediment concentrations (SSC) and yields (SSY) from undisturbed and human-disturbed portions of a small watershed in the south Pacific during storm and non-storm periods. The research questions addressed under this objective include: How much has human disturbance increased suspended sediment yield to the coast during storm events? What human activities dominate the anthropogenic contribution to suspended sediment yield? How do concentrations vary between storm and non-storm periods? Objective 2) Develop an empirical model of SSY during storm events (SSYEV). This objective will answer the questions: Which storm metric is the best predictor of SSYEV: total event precipitation, Erosivity Index, total event discharge, or maximum event discharge? How do sediment contributions from undisturbed areas and human-disturbed areas vary with storm size? Objective 3) Estimate annual sediment yields and compare with other volcanic tropical islands. This objective will use the measured SSYEV results from Objective 1, and modeling results from Objective 2 to estimate annual sediment yields from the study watersheds, for comparison with other literature on volcanic tropical islands and disturbed watersheds.

## 2. Study Area

The study watershed, Faga’alu, is located on Tutuila (14S, 170W), American Samoa. Tutuila has steep, heavily forested mountains with villages and roads mostly confined to the flat areas near the coast. 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 and several small ephemeral streams that drain directly to the bay (0.63 km²) (grey dotted boundary in Figure 1, “Admin.”). The main stream in Faga'alu (~3 km length) drains an area of 1.78 km² into Faga'alu Bay (area draining to FG3 in Figure 1, “Total” watershed), and can be divided into an undisturbed watershed (area draining to FG1, “Upper”), and a disturbed watershed including an aggregate quarry and an urban area (area draining to FG3, “Lower”). The Lower watershed can be further subdivided to isolate the impact of the quarry (area draining between FG1 and FG2, “Lower\_Quarry”), and the urban area, Faga’alu Village (area draining between FG2 and FG3, “Lower\_Village”) (Figure 1).

<Figure 1 here please>

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 about 3,800 mm on the coastal plain (Craig, 2009; Dames & Moore, 1981; Perreault, 2010; Tonkin & Taylor International Ltd., 1989; Wong, 1996). There are two subtle rainfall seasons: a drier winter season from June through September that accounts for 25% of annual precipitation and a wetter summer season, 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 rainfall is lower in the drier season, large storm events are still observed. At 11 sites around the island, 35% of annual peak flows occurred during the drier season over 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 (94.8%), including forest (85.7%) and scrub/shrub (9.0%) on the steep hillsides (Table 1). The Upper watershed, draining to FG1 in Figure 1, is dominated by undisturbed rainforest on steep hillslopes. The Lower subwatershed, draining areas between FG1 and FG3 in Figure 1, has steep vegetated hillslopes and a relatively small flat area in the valley bottom that is urbanized (3.2% of the watershed area "High Intensity Developed" in Table 1). A small portion of Faga’alu watershed (0.9%) is developed open space, which includes landscaped lawns and parks. In addition to some small household gardens there are several small agricultural areas of banana and taro on the steep hillsides. These agricultural plots were classified as grassland (0.2% GA, Table 1) due to the high fractional grass cover in the plots. There are several small footpaths and unpaved driveways in the village, but most unpaved roads are stabilized with compacted gravel and do not appear to be a major contributor of sediment (Horsley-Witten, 2012).

<Table 1 here please>

#### 2.2.2 Aggregate quarry and reservoirs

An open-pit aggregate quarry covers 1.6 ha and accounts for nearly all of the bare land (1.1% of Faga’aluwatershed) (Table 1). The quarry has been in continuous operation since the 1960's (Latinis et al., 1996). With few sediment runoff controls in place, sediment has been discharged directly to Faga'alu stream. In 2011, the quarry operators installed some sediment runoff management practices such as silt fences and small settling ponds (Horsley-Witten, 2011) but they were unmaintained and inadequate to control the large amount of sediment mobilized during storm events (Horsley-Witten, 2012). During the study period (2012-2014), additional sediment control measures were installed and some large piles of overburden were overgrown by vegetation (Figure 2), altering the sediment availability. In late 2014, large sediment retention ponds were installed to mitigate sediment runoff, but these mitigation activities happened after the sample collection reported here. See Holst-Rice et al. (2015) for a full description of sediment mitigation efforts at the quarry.

<Figure 2 here please>

Three water impoundment structures were built in the early 20th century in the upper part of the watershed for drinking water supply and hydropower, but none are in use and the one at FG1 is filled with sediment. We assume the other reservoirs are similarly filled with coarse sediment and are not currently retaining fine suspended sediment. A full description of stream impoundments is in Appendix A.

## 3. Methods

The field methods to measure precipitation (P), discharge (Q), suspended sediment concentration (SSC) and event-wise suspended sediment yield (SSYEV) 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,

SSYEV at FG1-3 was calculated from data on Q from stage data and stage-Q relationships, and SSC measured directly or modeled from T data and T-SSC relationships. Storm events were identified from the hydrographs at FG1 and FG3.

SSYEV contributions from subwatersheds were calculated by subtracting the contribution of the upstream subwatershed: 1) SSYEV from the Upper watershed was measured at FG1, 2) SSYEV from the Lower\_Quarry watershed was calculated as the difference between SSYEV measured at FG1 and at FG2, 3) SSYEV from the Lower\_Village was calculated as the difference between SSYEV measured at FG2 and at FG3, and 4) SSYEV from the Lower watershed (including the Lower\_Quarry and Lower\_Village subwatersheds) was calculated as the difference between SSYEV measured at FG1 and at FG3. SSYEV from the Total watershed was SSYEV measured at FG3. The impact of human disturbance was assessed using estimates of SSY from disturbed portions of the watershed and the Disturbance Ratio (DR).

Empirical, log-linear models to predict SSYEV from storm metrics (P and Q) were developed for the undisturbed (“Upper”) and disturbed watersheds (“Total”). These models and the ratio of annual storm precipitation to the precipitation during storms where SSYEV was measured were both used to estimate annual SSYEV from the Total watershed.

### 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.

We use the measured sediment yield at three locations to quantify the in-stream suspended sediment budget. Other components of sediment budgets include channel erosion and or channel and floodplain deposition (Walling and Collins, 2008), which were not measured in this study. Sediment storage and remobilization can significantly complicate the interpretation of in-stream loads, and complicate the identification of a land use signal. In Faga'alu, the channel bed is predominantly large volcanic cobbles and coarse gravel, with no significant deposits of fine sediment. Upstream of the village, the valley is very narrow with no floodplain. In the downstream reaches of the lower watershed, where fines might deposit in the floodplain, 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, so the measured sediment yields at the three locations reflect differences in hillslope sediment supply. Minimal sediment storage also reduces the lag time between landscape disturbance and observation of sediment at the watershed outlet.

#### 3.1.1. Precipitation (P)

P was measured at three locations in Faga'alu watershed using 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 a relationship between elevation and precipitation in the LOWER subwatershed. The total event precipitation (Psum) and event Erosivity Index (EI30) (Kinnell, 2013) were calculated using 1 min interval data from RG1, with data gaps filled by 15 minute interval precipitation data from Wx.

#### 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 measurements at 15 minute intervals using HOBO and Solinst pressure transducers (PT) and a stage-Q rating curve calibrated to manual 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). The PTs recorded stages that exceeded the highest stage with manually-measured Q, 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 to predict flow. At FG1, the HEC-RAS model was used to create the stage-Q relationship (Brunner, 2010). See Appendix B for details of the cross sections and rating curves developed 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 (m³/0.9 km²) and the watershed area draining to FG2 (1.17 km²). The specific water discharge from the subwatershed above FG2 is assumed be the same as above FG1 since average slopes, vegetation, and soils are 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 measured from water samples, or 2) turbidity data (T) recorded at 15 minute intervals and a T-SSC relationship calibrated to stream water samples collected over a range of Q and SSC. 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 stage height sensor. The Autosampler inlet tubing was positioned facing down-stream, just below the stage height sensor, approximately 30 cm above the stream bed, on rebar positioned near the middle of the stream. 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 values from grab samples was performed if at least three stream water samples were collected during a storm event (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 grab sample data 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 protective PVC housings near the streambed where the turbidity probe would be submerged at all flow conditions, with the turbidity probe oriented downstream. Despite regular maintenance, debris fouling during storm and baseflows was common and caused data loss during several storm events (Lewis et al., 2001).

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 and organic matter, temperature, and the shape, size, and composition of sediment. 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 grab samples under storm conditions (Lewis, 1996). A unique, linear T-SSC relationship was developed for each turbidimeter, at each location, using T data and SSC samples from storm periods only (r² 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 calculated with other sources of uncertainty in the following section.

#### 3.1.4. Cumulative Probable Error (PE)

Uncertainty in SSYEV estimates arises from both measurement and model errors, including stage-Q and T-SSC (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 to the final SSYEV 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:

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| --- | --- | --- |
|  |  | Equation 2 |
| where *PE* is the cumulative probable error for individual measured values (±%), *EQmeas* is uncertainty in Q measurements (±%), *ESSCmeas* is uncertainty in SSC measurements (± %), *EQmod* is uncertainty in Q modeled by the Stage-Q relationship (RMSE, as ±% of the mean observed Q), *ESSCmod* is uncertainty in SSC modeled by the T-SSC relationship or from interpolating over a time interval (RMSE, as ± % of the mean observed SSC) (Harmel et al., 2009). | | |

EQmeas and ESSCmeas were estimated using lookup tables from the DUET-H/WQ software tool (Harmel et al., 2009). The effect of uncertain SSYEV estimates may complicate conclusions about contributions from subwatersheds, anthropogenic impacts, and SSYEV-Storm Metric relationships. This is common in sediment yield studies where successful models estimate SSY with ±50-100% accuracy (Duvert et al., 2012) but the difference in SSY from undisturbed and disturbed areas was expected to be much larger than the cumulative uncertainty. PE was calculated for SSYEV from the UPPER and TOTAL watersheds, but not calculated for SSYEV from the LOWER subwatershed since it was calculated as the difference of SSYEV\_UPPER and SSYEV\_TOTAL.

### 3.2 Compare SSYEV for disturbed and undisturbed subwatersheds

Stream discharge (Q) and suspended sediment concentrations (SSC) and yields (SSY) were measured during both storm and interstorm periods at three sampling points that define three subwatersheds with different land covers. The UPPER subwatershed is sampled at FG1 and drains undisturbed forest; the LOWER\_QUARRY subwatershed is sampled at FG2 and drains the forest and quarry between FG1 and FG2; the LOWER\_VILLAGE subwatershed is sampled at FG3 and drains undisturbed forest and the village between FG2 and FG3; the LOWER subwatershed is sampled at FG3 and includes the undisturbed forest, quarry and village between FG1 and FG3. (Figure 1; Table 1). FG3 is also the watershed outlet for the TOTAL watershed.

#### 3.2.1. Suspended Sediment Yield during storm events (SSYEV)

SSY during individual storm events (SSYEV) were calculated at FG1-3 by integrating continuous estimates of SSY, calculated from measured or modeled water discharge (Q) and measured or modeled suspended sediment concentration (SSC) (Duvert et al., 2012):

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| --- | --- | --- |
|  |  | Equation 1 |
| where *SSYEV* 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). | | |

Storm events can be defined by precipitation (Hicks, 1990) or discharge parameters (Duvert et al., 2012), and the method used to identify storm events on the hydrograph can significantly influence the analysis of SSYEV (Gellis, 2013). Due to the large number of storm events and the prevalence of complex storm events recorded 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 includes both undisturbed and human-disturbed surfaces. SSYEV from disturbed areas only was estimated as:

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| --- | --- | --- |
|  |  | Equation 3 |
| where *SSYEV\_distrb* is SSYEV from disturbed areas only (tons), *SSYEV\_subws* is SSYEV (tons) measured from the LOWER subwatershed (e.g. SSYEV\_FG3- SSYEV\_FG2), *sSSYEV\_UPPER* is specific SSYEV (tons/km2) from the UPPER subwatershed (SSYEV\_FG1), and *Areaundist* is the area of undisturbed forest in the LOWER subwatershed (km2). Similar calculations were made for the LOWER\_QUARRY and LOWER\_VILLAGE subwatersheds to isolate the contributions from the disturbed quarry and village. | | |

The disturbance ratio (DR) is the ratio of SSYEV under current conditions to SSYEV under pre-disturbance conditions:

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| --- | --- | --- |
|  |  | Equation 4 |
| where Asubw is the area of the subwatershed. | | |

Both Equations 3 and 4 assume that sSSYEV from forested areas in the LOWER subwatershed equals sSSYEV from the undisturbed UPPER watershed.

### 3.3 Modeling SSYEV with storm metrics

The relationship between SSYEV and storm metrics can be modelled by a power law function (log-linear):

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| --- | --- | --- |
|  |  | 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 *SSYEV* and *X* (Basher et al., 2011; Duvert et al., 2012; Hicks, 1990). Model fits for each storm metric were compared using coefficients of determination (r2) and Root Mean Square Error (RMSE). The correlation between storm metrics (X) and SSYEV was also quantified using both parametric (Pearson) and non-parametric (Spearman) correlation coefficients.  Four storm metrics were tested as predictors of SSYEV: total event precipitation (Psum), event Erosivity Index (EI30) (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). SSYEV 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 watershed indicates higher sediment yield for the same size storm event, compared to sediment yield from the undisturbed watershed. A difference in slope (β) would indicate the relative sediment contributions from the subwatersheds change with increasing storm size.

### 3.4. Estimation of annual SSY

Annual SSY and sSSY were estimated using two methods: the empirical storm metric-SSY models, and the ratio of annual storm precipitation to the precipitation measured during storms where SSYEV was measured.

A continuous annual time-series of SSY was not possible at the study site due to the discontinuous field campaigns and failure of or damage to the instruments during some months. Continuous records of P and Q were available for 2014, so the Psum-SSYEV and Qmax-SSYEV models (Equation 5) were used to predict SSYEV for all storms in 2014 (Basher et al., 1997). Construction of sediment mitigation structures at the quarry began in October 2014, greatly reducing SSYEV from the LOWER\_QUARRY subwatershed (Messina and Biggs, forthcoming), so the Qmax-SSYEV relationship developed prior to the mitigation was used to calculate the annual pre-mitigation sediment yield. For storms missing Qmax data at FG3, Qmax was predicted from a linear regression between Qmax at FG1 and Qmax at FG3 for the study period (R2 =0.88).

Annual SSY and sSSY were also estimated by multiplying SSYEV from measured storms by the ratio of annual storm precipitation (PEVann) to the precipitation measured during storms where SSYEV was measured (PEVmeas):

|  |  |  |
| --- | --- | --- |
|  |  | Equation 6 |
| where *SSYann* is estimated annual SSY from storms, *SSYEV\_meas* is SSYEV from sampled storms (all, Tables 2 and 4), PEVmeas is precipitation measured during the sampled storms, and PEVannis the precipitation during all storm events defined by the hydrograph separation. Equation 6 assumes that the sediment yield per mm of storm precipitation is constant over the year, and that the size distribution of storms has no effect on SSYEV, though there is some evidence that SSYEV 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

Annual precipitation (P) measured at RG1 was 3,502 mm, 3,529 mm, and 3,709 mm in 2012, 2013, and 2014, respectively, which averages 94% of long-term precipitation (=3,800 mm) from PRISM data (Craig, 2009). Linear relationships between daily P at RG1 and Wx (slope=0.95, r2=0.87) and RG1 and RG2 (slope=0.75, r2=0.85) were observed, so P was assumed to be homogenous over the watershed for all analyses. The lower P measured at RG2 was assumed to be caused by surrounding vegetation, as the only available installation location was in a forest clearing with high surrounding canopy. Rain gauges could only be placed as high as ~300 m (RG2), though the highest point in the watershed is ~600 m. Long-term rain gage records show a strong precipitation gradient with increasing elevation, with average annual P of 3,000-4,000 mm on the lowlands, increasing to more than 6,350 mm at high elevations (>400 m.a.s.l.) (Craig, 2009; Dames & Moore, 1981; Wong, 1996). P data measured at higher elevations would be useful to determine the orographic effect. For this analysis, however, the absolute values of P in each subwatershed are not important since P and the Erosivity Index are only used as predictive storm metrics for Objective 2.

#### 4.1.2 Water Discharge (Q)

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

< Figure 3 here please>

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

<Figure 4 here please>

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). A single storm event from 2/14/2014 (Figure 4) shows that SSC was highest at FG2 on the rising limb of the hydrograph, and that turbidity and SSC at FG3 were always higher than at FG1 throughout the storm event. Mean (μ) and maximum SSC of all water samples, including those collected during both storm and non-storm periods, were lowest at FG1 (μ=28 mg/L, max=500 mg/L, n=59), highest at FG2 (μ=337 mg/L, max=12,600 mg/L, n=90 grab samples, n=198 from the Autosampler), and intermediate at FG3 (μ=148 mg/L, max=3,500 mg/L, n=159). SSC collected during non-storm periods were lowest at FG1, highest at FG2 (n=21), and in between at FG3 (n=45) (Figure 5a). Similarly, SSC during storms was highest at FG1 (n=45), highest at FG 2, (n=69) and intermediate at FG3 (n=120). SSC data collected at FG1, FG2 and FG3 were highly non-normal, so non-parametric tests for statistical significance were applied. SSC was statistically significantly different among the three sampled site during non-storms (p<10-4) 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 between FG2 and FG3 were significant 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). At FG1, variability of SSC during stormflow was assumed to be caused by randomly occurring landslides or mobilization of sediment stored in the watershed during large storm events. The maximum SSC at FG1 (500 mg/L), was sampled on 04/23/2013 at high discharge (QFG1= 3,724 L/sec) (Figure 6a). Anecdotal and field observations reported higher than normal SSC upstream of the quarry during the 2013 field season, possibly due to landsliding from previous large storms (G. Poysky, pers. comm.).

<Figure 6 here please>

At FG2 and FG3, additional variability in the Q-SSC relationship was due to the changing sediment availability associated with quarrying operations and construction in the village. The high SSC values observed downstream of the quarry (FG2) during low Q were caused by two mechanisms: 1) precipitation events that did not result in stormflow as defined by the hydrograph separation algorithm, but generated runoff from the quarry with high SSC and 2) washing fine sediment into the stream during rock crushing operations at the quarry.

The maximum SSC sampled at FG2 (12,600 mg/L) and FG3 (3,500 mg/L) were sampled during the same rainfall event (03/05/2012), but during low Q (Figure 6b-c). During this event, brief but intense precipitation caused high sediment runoff from the quarry. SSC was diluted further downstream of the quarry at FG3 by the addition of runoff with lower SSC from the village.

#### 4.1.4 Cumulative Probable Error (PE)

Cumulative Probable Error (RMSE %) for SSYEV estimates were calculated from the measurement errors for Q (8.5%) and SSC grab samples (16.3%), and the model errors of the respective stage-Q and T-SSC relationships for that location. Cumulative Probable Errors (PE) in SSYEV were 28-49% (μ=43%) at FG1 and 36-118% (μ=94%) at FG3.

The measurement error (RMSE) for Q at FG1 and FG3 was 8.5 %, which included error in the 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)). The model errors (RMSE) were 32% for the stage-Q rating curve using Manning's equation at FG3, and 22% using HEC-RAS at FG1.

The measurement error (RMSE) for SSC was 16.3%, which included errors for sample collection and analysis. Sample collection error consisted of interpolating over a 30 min interval (5%) and sampling during stormflows (3%). Sample analysis error was from measuring SSC by filtration (3.9%). The model errors (RMSE) 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 SSYEV for disturbed and undisturbed subwatersheds

#### 4.2.1. Suspended sediment yield during storm events (SSYEV) from Upper, Lower, and Total watersheds

A total of 210 storm events were identified using hydrograph separation on the Q data at FG1 and FG3 between January, 2012, and December 2014. A total of 169 events 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 events (FG3). Of those storms, 42 events had data for P, Q, and SSC at both FG1 and FG3. SSY data from interpolated grab samples were collected at FG2 for 8 storms to calculate SSYEV from the LOWER\_QUARRY and LOWER\_VILLAGE subwatersheds separately. Storm event durations ranged from 1 hour to 2 days, with mean duration of 13 hours.

For the 42 storms with complete data at both FG1 and FG3 (Table 2), SSYEV\_TOTAL was 129±121 tons, with 17±7 tons from the UPPER subwatershed and 112 tons from the LOWER subwatershed. The UPPER and LOWER subwatersheds are similar in size (0.90 km² and 0.88 km²) but SSYEV\_LOWER accounted for 87% of SSYEV at the watershed outlet (Table 2). The DR estimated using Equation 4, with sSSYEV\_UPPER = 18.8 tons/km², suggests sSSYEV has increased by 6.8x in the LOWER subwatershed, and 3.9x for the TOTAL watershed compared with undisturbed forest.

<Table 2 here please>

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

Disturbed areas accounted for 10% of the LOWER subwatershed area but approximately 87% of the SSYEV from the LOWER subwatershed. Only 5.2% of the TOTAL watershed area was disturbed, but SSY from disturbed areas accounted for 75% of SSY EV\_TOTAL. sSSY from disturbed areas in the LOWER subwatershed was 1,095 tons/km², or 58x the sSSY of undisturbed forest (Table 3).

<Table 3 here please>

#### 4.2.3. Suspended sediment yield during storm events (SSYEV) from Lower\_Quarry and Lower\_Village watersheds

The separate contributions to SSY from the quarry and village were determined for eight storm events (Table 4), where 29% of SSYEV came from the UPPER subwatershed, 36% from the LOWER\_QUARRY subwatershed, and 35% from the LOWER\_VILLAGE subwatershed. sSSY from the UPPER, LOWER\_QUARRY, and LOWER\_VILLAGE subwatersheds, and the TOTAL watershed was 15, 61, 27, and 26 tons/km², respectively. The storms in Table 4 show a smaller increase in SSY from the TOTAL watershed (1.7x SSYUPPER) compared with the 42 storms with data at FG1 and FG3 (3.9x SSYUPPER Table 2), so these storms may underrepresent the contributions of the quarry and village to SSY. sSSY increased by 4.1x in the LOWER\_QUARRY subwatershed and 1.8x 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 watershedsVery small fractions of the subwatershed areas are disturbed, yet roughly 77% of SSY EV\_LOWER\_QUARRY (6.5% disturbed) and 51% of SSY EV\_LOWER\_VILLAGE (11.7% disturbed) subwatersheds was from disturbed areas. Similarly, 5.2% of the TOTAL watershed was disturbed but 75-45% of SSY EV\_TOTAL was from disturbed areas (Tables 3 and 5). The quarry significantly increased SSY and contributed the majority of SSY from disturbed areas in Faga'alu watershed. sSSY from disturbed areas in the UPPER (37 tons/km²), LOWER\_QUARRY (722 tons/km²), and LOWER\_VILLAGE subwatersheds (116 tons/km²) suggested that disturbed areas increase sSSY over forested conditions by 49x and 8x in the LOWER\_QUARRY and LOWER\_VILLAGE subwatersheds, respectively. Human disturbance in the LOWER\_VILLAGE subwatershed also increased SSY above natural levels but the magnitude of disturbance was much lower than the quarry.

<Table 5 here please>

### 4.3 Modeling SSYEV with storm metrics

#### 4.3.1. Selecting the best predictor of SSYEV

Qsum and Qmax were the best predictors of SSYEV for the forested UPPER watershed, and Psum and Qmax were the best predictors for the TOTAL watershed (Figure 7, Table 6). SSYEV is calculated from Q so it is expected that Qsum should correlate closely with SSYEV (Duvert et al., 2012; Rankl, 2004). Discharge metrics were also highly correlated with SSYEV in the TOTAL watershed, suggesting discharge metrics are good predictors in both disturbed and undisturbed watersheds. Most of the scatter in the Qmax-SSYEV relationship is observed for small events, and Qmax correlated strongly with the largest SSYEV values, when most of the annual sediment load is generated (Table 6).

<Table 6 here please>

Precipitation was measured at the quarry, which may reflect precipitation characteristics more accurately in the LOWER than the UPPER watershed, and account for the lower correlation coefficients between precipitation and SSYEV\_UPPER. SSY from the LOWER subwatershed is hypothesized to be mostly generated by hillslope erosion by sheetwash and rill formation at the quarry and on dirt roads, and agricultural plots, whereas SSY from the UPPER subwatershed is hypothesized to be mainly 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 SSYEV and Qmax in both watersheds, Qmax may be a promising predictor that integrates both precipitation and discharge processes.

#### 4.3.2. Effect of event size and watershed disturbance

SSYEV from the TOTAL watershed was higher than from the UPPER watershed for the full range of measured storms with the exception of a few events that are considered outliers. The outlier events could be attributed to measurement error or to landslides or other mass movements in the UPPER subwatershed. The separation of multi-peak storm events, storm sequence, and antecedent conditions may also play a role. While the climate on Tutuila is tropical, without strong seasonality, periods of low rainfall can persist for several weeks, perhaps altering the water and sediment dynamics in the subsequent storm events.

All storm metric-SSYEV model intercepts (α) were significantly different (p<0.01), but only the Qsum-SSYEV model showed significantly different slopes (β, p<0.01) (Figure 7, Table 6). The Qsum-SSYEV models indicate that SSYEV from the UPPER and TOTAL watersheds converge at higher Qsum values. Conversely, the Psum- and Qmax-SSYEV models show no change in relative contributions of SSY over the range of storm sizes (Figure 7).

<Figure 7 here please>

The relative contribution of SSY from the human-disturbed watershed was hypothesized to diminish with increasing storm size. The results from precipitation metrics and discharge metrics were contradictory. The relative contribution of SSYEV from the human-disturbed watershed decreases with storm size in the Qsum-SSYEV model, but the Psum- and Qmax-SSYEV models show no change in relative contributions over increasing storm size (Figure 7). It was hypothesized that SSYEV from undisturbed forest areas would become the dominant source for larger storm events, but the DR remains high for large storm events due to the naturally low SSYEV from natural 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

Estimates of annual sSSY depended on which predictor was used to estimate SSYEV. The Psum model resulted in a much lower estimate of sSSY than the Qmax model (Table 7). The large difference in sSSY between the two methods was due to higher scatter about the Psum-SSYEV relationship for large events compared with the Qmax-SSYEV, and the Qmax model is likely more robust. Annual SSY was also calculated for 2014 using Equation 6 for three sets of storm events: a) all events with SSYEV data, including those where SSYEV data were only available for a single site; b) only events where data was available for both UPPER (FG1) and TOTAL (FG3) and c) only events where data was available for UPPER (FG1), LOWER\_QUARRY (FG2), and TOTAL (FG3). Including all storms (method a) will provide the best estimate at a given location, while b) and c) allow more direct comparison of different subwatersheds.

<Table 7 here please>

Annual storm precipitation (PEVann) 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 hydrograph separation method used here. All storms with measured SSYEV at FG1 from 2012-2014 included 3,457 mm of precipitation (PEVmeas), or 125% of PEVann, so estimated annual SSY from the UPPER subwatershed from Equation 6 was 41 tons/yr (45 tons/km²/yr). All storms with measured SSYEV at FG3 from 2012-2014 included 2,628 mm of precipitation, or 95% of expected annual storm precipitation so estimated annual SSY from the TOTAL watershed was 428 tons/yr (241 tons/km²/yr).

Overall, the Qmax model and Equation 6 using all events gave similar estimates of annual SSY at both the UPPER watershed (41-61 tons/yr) and the TOTAL watershed (428-439 tons/yr). The accuracy of the Psum model was compromised by significant scatter for large events, while the Qsum model had significantly less scatter for large events. The eight storms sampled at all three locations (Table 4) had unusually high loads from the UPPER watershed but similar SSY from the LOWER watershed, likely resulting in a low estimate of sediment loading and DR from the quarry.

## 5. Discussion

### 5.1 Compare SSC and SSYEV for disturbed and undisturbed subwatersheds

Given the close proximity of the quarry to the stream, SSC downstream of the quarry can be 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). Riverine discharge of fine sediment rinsed from aggregate was discontinued in 2013. In 2013 and 2014, waste sediment was piled on-site and severe erosion of these changing stockpiles caused high SSC only during storm events.

Event wise analysis of SSYEV was useful because hysteresis and interstorm variability caused significant scatter in the instantaneous Q-SSC relationship, which is common in many watersheds (Asselman, 2000; Stock and Tribble, 2010). 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.

The SSYEV approach is useful for determinining change over space and time without problems of interannual variability in precipitation totals or the need for one or several years of continuous monitoring. From a management perspective, the event-wise 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.

### 5.2 Modeling SSYEV with storm metrics

Several researchers have attempted to explain values of the intercept (α) and slope (β) coefficients of the sediment rating curve as a function of watershed characteristics. A traditional sediment rating curve (Q-SSC) is considered a 'black box' model, and though the slope and intercept have no physical meaning, some physical interpretation has been ascribed to them (Asselman, 2000). Rankl (2004) hypothesized that the intercept in the Qmax-SSYEV relationship varied with sediment availability and erodibility in watersheds. 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 (Rankl, 2004), intercepts of the SSYEV-Qmax relationship ranged from 111-4,320 (Qmax in m³/s/km², SSYEV in Mg/km²). In eight sub-humid to semi-arid watersheds (0.45-22 km²) (Duvert et al., 2012), the intercepts ranged from 25-5,039. In Faga'alu, the intercept in the undisturbed, UPPER subwatershed was 0.35, and in the disturbed, TOTAL watershed the intercept was 1.38, which are an order of magnitude or two lower than the lowest intercepts in Rankl (2004) and Duvert et al. (2012). This suggests that sediment availability is relatively low in Faga'alu, under natural and human-disturbed conditions, likely due to the dense forest cover.

High slope values in the log-log plots (β coefficient) suggest that small changes in stream discharge lead to large increases in sediment load due to the erosive power of the river 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 ranged from 1.07-1.29 in five semi-arid to arid watersheds in Wyoming, and were not statistically different among watersheds. In the 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) compiled by Duvert et al. (2012). In Faga'alu, slopes were 1.51 and 1.40 in the UPPER and TOTAL watersheds, respectively. These slopes are very consistent with the slopes presented in Rankl (2004) and Duvert et al. (2012), despite large differences in climate and land cover.

In Faga'alu, SSYEV was least correlated with the Erosivity Index (EI30). Duvert et al. (2012) also found low correlation coefficients with 5 min rainfall intensity for 8 watersheds in France and Mexico. Rodrigues et al. (2013) hypothesized that EI30 is poorly correlated with SSYEV due to the effect of previous events on antecedent moisture conditions and in-channel sediment storage. Cox et al. (2006) found EI30 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 SSYEV at Faga'alu were observed for discharge metrics Qsum and Qmax (Basher et al., 2011; Duvert et al., 2012; Fahey et al., 2003; Hicks, 1990; Rankl, 2004; Rodrigues et al., 2013). While Qsum and Psum had higher correlations in individual watersheds, Qmax was a good predictor of SSYEV in both the disturbed and undisturbed watershed.

### 5.3 Estimation of annual SSY and comparison with other tropical islands

Sediment yield is highly variable among individual 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 ~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 activity in the UPPER Faga'alu subwatershed, its sSSY should be lower than sSSY from watersheds presented in Milliman and Syvitski (1992), which included watersheds with human disturbance. 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), though 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 a much smaller watershed and the study period was relativtly short compared to others included in their models.

Sediment yield has been measured using modern fluvial measurements similar to ours for two Hawaiian watersheds: Hanalei watershed on Kauai (“Hanalei”), and Kawela watershed on Molokai (“Kawela”) (Table 8) (Ferrier et al., 2013; Stock and Tribble, 2010). Hanalei (54 km²) has steep relief and mean areal precipitation of 3,866 mm/yr (Ferrier et al., 2013), which is slightly higher than rainfall at Faga’alu during our two year monitoring period (3,247 mm/yr). Over a four year period, SSC at Hanalei averaged 63 mg/L and reached a maximum of 2,750 mg/L (Stock and Tribble, 2010), which is slightly lower than observations at the outlet of Faga’alu over a two year period (mean 148 mg/L, maximum 3,500 mg/L). Using fluvial data over a 3 month period as well as longer-term geologic methods, Calhoun and Fletcher (1999) estimated sSSY from Hanalei as 140±55 tons/km²/yr, but had fewer data than Stock and Tribble (2010), who estimated sSSY as 525 tons/km²/yr. Ferrier et al., (2013) reported annual suspended sediment yield at Hanalei as 369 ± 114 tons/km2/yr over a 6 year period. These values are higher than observed from the undisturbed subwatershed in Faga’alu (45-68 tons/km2/yr) but similar to the disturbed (430-441 tons/km2/yr) subwatersheds. Rocks at Hanalei are of similar age (1.5 Mya) or older (3.95-4.43 Mya) (Ferrier et al., 2013) compared with Faga’alu (1.2 Mya) (McDougall, 1985), so landscape age does not explain the difference in observed SSY between Hanalei and Faga’alu. Kawela (14 km²) is disturbed by grazing and is in a sub-humid climate, where precipitation varies with elevation from 500-3,000 mm. Stock and Tribble (2010) estimated sSSY from Kawela was 459 tons/km²/yr, which is similar to the disturbed subwatershed in Faga’alu, but nearly twice as high as the TOTAL Faga’alu watershed. In Kawela, SSC (mean 3,490 mg/L, maximum 54,000 mg/L) was much higher than measured in Faga'alu TOTAL watershed, so the difference in SSY is due in part to higher SSC rather than to higher observed runoff. Overall, both Hawaiian watersheds have higher SSY than Faga’alu, which is consistent with the low intercepts of Faga’alu in the Qmax-SSYEV relationships, and suggests that Faga’alu may have uniquely 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>

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.

### 5.4 Comparison with other kinds of sediment disturbance

SSY at Faga’alu was increased by 3.9x compared with the natural background. Other studies in small, mountainous watersheds have documented one to several orders of magnitude increases in SSY from land use that disturbs a small fraction of the watershed area. Urbanization and mining can increase sediment yield by two to three orders of magnitudes in catchments of several km². Yields from construction sites can exceed those 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 have resulted in increases in total SSY to coral environments, similar to Faga’alu. The development of the Great Barrier Reef (GBR) catchment (423,000 km2) since European settlement (ca.1830) led to increases in SSY by an estimated factor of 5.5x (Kroon et al., 2012). 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 identified as a source of sediment 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.

## 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. Qmax was a good predictor of SSYEV in both the disturbed and undisturbed watersheds, making it a promising predictor in diverse environments. The slopes of the Qmax-SSYEV 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. The event-wise approach did not require continuous in situ monitoring for a single or multiple years, which would not have been logistically possible in this remote study area. 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.

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