# 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) during storm and non-storm periods, 2012-2014, were measured 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 (10.1% disturbed) accounted for an average of 87% of SSYEV from the watershed. Observed sediment yield (mass) to the coast, including human disturbed subwatersheds, was 3.9x the natural background. Specific SSY (mass/area) from the disturbed quarry area was 49x higher than from natural forest compared with 8x higher from the village area. 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 the Erosivity Index. Best estimates of annual SSY varied by method, from 45-143 tons/km²/yr from the undisturbed subwatershed, 441-598 tons/km²/yr from the human-disturbed subwatershed, and 241-368 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 SSYEV. Given the limited access to gravel for infrastructure development, sediment disturbance from local aggregate mining may be a critical sediment source on remote islands in the Pacific and elsewhere. Identification of erosion hotspots like the quarry using rapid, event-wise measures of suspended sediment yield will help efforts to mitigate sediment stress and restore coral reefs.

## Keywords:

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

## 1. Introduction

Human disturbances 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 yields 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 and steep slopes (Milliman and Syvitski, 1992). The steep topography and small floodplains on small volcanic islands limits sediment storage and the buffering capacity of the watershed against increased hillslope sediment supply (Walling, 1999). Such environments characterize many volcanic islands in the South Pacific and elsewhere where many coral reefs are sediment-stressed (Bégin et al., 2014; Fallon et al., 2002; Hettler et al., 1997; Rotmann and Thomas, 2012).

A large proportion of sediment yield can originate from disturbances that cover small fractions of the watershed area, 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% of the watershed area, and 50% of the sediment originated from only 1% of the watershed (Risk, 2014; Stock et al., 2010). On St. John in the Caribbean, unpaved roads covering 0.3-0.9% of the watershed were the dominant sediment source, 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 yielded 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. 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 remote environments. Existing erosion 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). Models that predict SSY from small, mountainous catchments would establish baselines for change-detection, and improve 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 (Ferguson et al., 1991; Gray et al., 2014; 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 disturbed watershed may decrease as it reaches steady-state, 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). The relative 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, 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 (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.

Event-wise SSY (SSYEV) 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 (Qmax). The EI quantifies the erosive energy of rainfall. 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.

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. How does SSC vary between storm and non-storm periods? How much has human disturbance increased SSY during storm events? Which land uses dominate the anthropogenic contribution to SSY?
2. Develop an empirical model to predict SSYEV from easily-monitored discharge or precipitation metrics. Which storm metric is the best predictor of SSYEV? How does human-disturbance to SSY vary with storm metric?
3. Estimate annual SSY using the measurements from Objective 1, and modeling results from Objective 2. How does SSY at the field site compare to other volcanic tropical islands and other disturbed watersheds?

## 2. Study Area

Faga’alu (Fong-uh ah-loo) 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 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 Mountain 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).

<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% of the watershed area) and 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 valley bottoms. The mean slope of Faga'alu watershed is 0.53 m/m and total relief is 653 m.

### 2.1 Climate

Annual precipitation (P) 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 accounts for 25% of annual P, and a wetter summer from October through May accounts for 75% of annual P (Craig, 2009; Perreault, 2010). P is lower in the drier season but large storms still occur: at 11 stream gages 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 (95%), including forest (86%) and scrub/shrub (9%) (Table 1). The Upper watershed is dominated by undisturbed rainforest (82%) 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 (6.4% "High Intensity Developed" in Table 1). A small portion of the watershed (1.8%) is developed open space, mainly landscaped lawns and parks. Agricultural areas include small household gardens and small areas of banana and taro on the steep hillsides, classified as grassland (0.3% 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 eroded from the quarry 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 coarse sediment. Other deep pools at the base of waterfalls in the upper watershed have no fine sediment and we assume the other reservoirs are not retaining fine suspended sediment. A full description of the reservoirs is in Appendix A.

## 3. Methods

The field methods used to calculate 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. Briefly, the in-stream suspended sediment yield (tons) and specific yield (SSY, tons/km2) were calculated for individual storm events (SSYEV) at three locations in Faga’alu watershed using calculated discharge (Q) and suspended sediment concentration (SSC)(Figure 1) (Section 3.1). Q was calculated from continuously recorded stage and a stage-discharge relationship calibrated with field measurements (Section 3.1.2). SSC was measured directly from grab samples or modeled from continuously monitored turbidity (T) and T-SSC relationships calibrated to in-stream SSC (Section 3.1.3). Storm events were identified using automated hydrograph separation, and SSYEV calculated for each monitored location with Q and SSC data (Section 3.2.1). The subwatersheds were nested, so SSYEV contributions from subwatersheds were calculated by subtracting SSYEV at the upstream subwatershed from SSYEV at the given downstream subwatershed. The sediment yield from disturbed surfaces was calculated assuming a uniform yield from forested parts of disturbed subwatersheds (Section 3.2.2). The cumulative probable error of SSYEV was calculated for each storm to incorporate errors in Q and SSC (Section 3.2.3). Log-linear regression models were developed to predict SSYEV from storm metrics for the undisturbed and disturbed subwatersheds (Section 3.3). Annual SSY was estimated from the regression models and the ratio of annual storm precipitation to the precipitation during storms where SSYEV was measured (Section 3.4).

Measurements of SSY at FG1, FG2 and FG3 quantify 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). 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.

### 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)

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

#### 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, so the HEC-RAS model was used to create the stage-Q relationship and calibrated to Q measurements (Brunner, 2010). See Appendix B for further details on 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 (m³/km²) and the watershed area draining to FG2 (1.17 km²). 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 stream 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 minute 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 µm 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 occurred frequently.

A unique, linear T-SSC relationship was developed for each turbidimeter, at each location, using linear regression on T data and SSC samples from storm periods (r² values 0.79-0.99, Appendix D). 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. T is a robust predictor of SSC in streams (Gippel, 1995), and is most accurate when a unique T-SSC relationship is developed for each instrument and field site separately, using in situ SSC samples during storms (Lewis, 1996; Minella et al., 2008). Errors were higher at FG3 (RMSE 112% for YSI, 46% for OBS), and lower at FG1 (RMSE 13% for YSI at FG1). The T-SSC relationship for the YSI predicted much higher SSC at FG3 than at FG1 for the same T value, which may show a spurious increase in SSC (and SSY) at FG3. However, T during storms was consistently higher at FG3 (μ=82, max=1,263) than at FG1 (μ=15, max=1,073). The critical assumption in our application is that the parameters of the T-SSC relationship are stable over time and among storm events. The T-SSC relationships are critical to SSY calculations, so the cumulative error from these relationships were combined with other error sources to estimate uncertainty in the SSYEV estimates (Section 3.2.3). See Appendix D for further details on T-SSC relationsihps at FG1 and FG3

### 3.2 SSYEV for disturbed and undisturbed watersheds

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

SSYEV was calculated at FG1, FG2 and FG3 by integrating continuous Q and SSC (Duvert et al., 2012):

|  |  |  |
| --- | --- | --- |
|  |  | 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 P (Hicks, 1990) or Q data (Duvert et al., 2012), and the method used to identify storm events can significantly influence the analysis of SSYEV (Gellis, 2013). Due to the large 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), which separates the hydrograph into quickflow, or direct surface or subsurface runoff that occurs during storms, and baseflow or delayed flow (Hewlett and Hibbert, 1967). Quickflow and baseflow components are not well defined in terms of hydrologic flowpath; here we use the separation operationally to define storm events. Spurious events were sometimes identified due to instrument noise, so only events with quickflow lasting at least one hour and peak quickflow greater than 10% of baseflow were included (See Appendix C for example).

The subwatersheds were nested (Figure 1), so SSYEV from subwatersheds was calculated as follows: SSYEV from the Upper subwatershed, draining undisturbed forest, was sampled at FG1; SSYEV from the Lower\_Quarry subwatershed, draining undisturbed forest and the quarry between FG1 and FG2, was calculated as the difference between SSYEV measured at FG1 and FG2; SSYEV from the Lower\_Village subwatershed, which drains undisturbed forest and the village between FG2 and FG3, was calculated as the difference between SSYEV 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 SSYEV measured at FG1 and FG3. SSYEV from the Total watershed was measured at FG3 (Figure 1; Table 1).

#### 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 forest and human-disturbed surfaces (Table 1). SSYEV from disturbed areas only was estimated as:

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| --- | --- | --- |
|  |  | Equation 2 |

where *SSYEV\_distrb* is SSYEV from disturbed areas only (tons), *SSYEV\_subws* is SSYEV (tons) measured from the subwatershed, *sSSYEV\_UPPER* is specific SSYEV (tons/km2) from the Upper subwatershed (SSYEV\_FG1), and *Areaundist* is the area of undisturbed forest in the subwatershed (km2). This calculation assumes that forests in all subwatersheds has SSY similar to the Upper watershed.

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

|  |  |  |
| --- | --- | --- |
|  |  | Equation 3 |

where *Asubw* is the area of the subwatershed. Both Equations 2 and 3 assume that sSSYEV from forested areas in the Lower subwatershed equals sSSYEV from the undisturbed Upper watershed and that pre-disturbance land cover was forested throughout the watershed.

#### 3.2.3 Error Analysis

Uncertainty in SSYEV calculations arises from errors in measured and modeled Q and SSC (Harmel et al., 2006). The root mean square error propagation 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 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:

|  |  |  |
| --- | --- | --- |
|  |  | Equation 4 |

where *PE* is the cumulative probable error for SSYEV estimates (±%), *EQmeas* is uncertainty in Q measurements (±%), *ESSCmeas* is uncertainty in SSC measurements (± %), *EQmod* is uncertainty in the Stage-Q relationship (RMSE, as ±% of the mean observed Q), *ESSCmod* is uncertainty in the T-SSC relationship or from interpolating SSC samples (RMSE, as ± % of the mean observed SSC) (Harmel et al., 2009).EQmeas and ESSCmeas were taken from the DUET-H/WQ software tool lookup tables (Harmel et al., 2009).

The effect of uncertain SSYEV estimates may complicate conclusions about anthropogenic impacts and storm metric-SSYEV relationships, but difference in SSYEV 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 (Calhoun and Fletcher, 1999; Duvert et al., 2012). PE was calculated for SSYEV from the Upper and Total watersheds, but not for the Lower subwatershed since it was calculated as the difference of SSYEV\_UPPER and SSYEV\_TOTAL.

### 3.3 Modeling SSYEV with storm metrics

The relationship between SSYEV and storm metrics was modelled as a log-linear function:

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| --- | --- | --- |
|  |  | Equation 5 |

where *X* is a storm metric, the regression coefficients α and β are obtained by ordinary least squares regression on the logarithms of *X* and SSYEV(Basher et al., 2011; Duvert et al., 2012; Hicks, 1990) and *BCF* is the Smearing bias correction factor for log-transformation bias (Duan, 2016; USGS and NRTWQ, 2016), which is recommended when residuals of the log-log regression are non-normal (Boning, 1992; Koch and Smillie, 1986). The Kolmogorov-Smirnov test showed our regression residuals were non-normally distributed.

Four storm metrics were tested as predictors of SSYEV: 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 and was calculated for each storm event identified in Section 3.2.1 following the methodology of Kinnell (2013) using only 1 min interval data at RG1. The discharge metrics (Qsum and Qmax) were normalized by watershed area to compare different sized subwatersheds.

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 were quantified using non-parametric (Spearman) correlation coefficients. 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).

### 3.4. Estimation of annual SSY

Annual SSY (mass) and sSSY (mass/area) were estimated using 1) the developed storm metric-SSYEV models, and 2) the ratio of annual storm precipitation to precipitation measured during storms with SSYEV 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 log-linear storm metric-SSYEV models (Equation 5), including log-bias correction (Duan, 2016; Ferguson, 1986), were used to predict SSYEV for all storms in 2014 (Basher et al., 1997). 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 precipitation 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), PEVannis the precipitation during all storm events in a year, and PEVmeas is precipitation during the set of sampled storms. 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 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

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). Daily P at RG1 was similar to P at Wx (regression slope=0.95, r2=0.87) and at RG2 (slope=0.75, r2=0.85). 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 forest clearing with high surrounding canopy. P 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 as 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 Lower subwatershed.

#### 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). Storm events were generally smaller but 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 on 2/14/2014 (Figure 4) shows that SSC at FG2 was highest on the rising limb of the hydrograph, and that T and SSC at FG3 were always higher than at FG1. SSC was consistently lowest at 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 and maximum SSC of all stream water samples 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), and intermediate at FG3 (μ=148 mg/L, max=3,500 mg/L, n=159). SSC data at FG1-3 were 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). FG2 and FG3 were significantly different for non-storm periods (p<0.05) but not for storms (p>0.10) due to the high variance.

<Figure 5 here please>

SSC varied by several orders of magnitude for a given Q at FG1-3 (Figure 6) due to significant hysteresis observed during storm periods (Figure 4). Maximum SSC at FG1 (500 mg/L) was sampled on 04/23/2013 at high Q (QFG1= 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 Q was low (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>

### 4.2 SSYEV 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 were recorded during 112 (FG1) and 74 storms (FG3). Of those storms, 42 had simultaneous P, Q, and SSC data at FG1 and FG3. Of those storms, only 8 had simultaneous P, Q, and SSC data at FG2. Storm events ranged from 1 hour to 2 days, with mean duration of 13 hours.

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

For the 42 storms with P, Q, and SSC data at both FG1 and FG3, SSYEV\_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 km² and 0.88 km²) but SSYEV\_LOWER accounted for 87% of SSYEV at the watershed outlet. The DR (Equation 4, 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 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 SSYEV\_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 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

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/km², respectively, with 29% of SSYEV 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 lower DR for the Total watershed (1.7x SSYUpper) compared with the 42 storms in Table 2 (3.9x SSYUpper). 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 watersheds

Disturbed areas cover small fractions of the subwatersheds, yet contributed roughly 77% of SSY EV\_LOWER\_QUARRY (6.5% disturbed) and 51% of SSY EV\_LOWER\_VILLAGE (11.7% disturbed). Similarly, disturbed areas cover 5.2% of the Total watershed but contributed 75-45% of SSY EV\_TOTAL (Tables 3 and 5). 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 increased SSYEV above natural levels but the magnitude of disturbance was much lower than the quarry.

<Table 5 here please>

#### 4.2.5 Error analysis

Cumulative Probable Errors (PE) in SSYEV, calculated from measurement and model errors in Q and SSC data, were 40-56% (μ=52%) at FG1 and 36-118% (μ=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 13% (3 mg/L) for the YSI and TS turbidimeters at FG1, 112% (342 mg/L) for the YSI turbidimeter at FG3, and 47% (46 mg/L) for the OBS turbidimeter at FG3.

SSC and resulting SSYEV estimates are sensitive to the slope of the T-SSC rating curve, so we tested the sensitivity of the DR and percent SSY contributions to different T-SSC rating curves. The slope of the T-SSC rating curve for the YSI, deployed at FG3 in 2012, was much higher at FG3 than at FG1 (Appendix D, Figure D.1a-b), which could lead to an overestimation of SSYEV and the DR for the Total watershed. Using the T-SSC relationship from FG1 to predict SSC at FG3 reduced the DR from 3.6 (Table 2) to 2.5, and changed the average SSYEV contributions from 13% to 20% from the Upper watershed, and from 87% to 80% from the Total watershed. We conclude that use of different T-SSC relationships does not significantly change our conclusions about the dominance of the lower watershed in the sediment load to the coast.

### 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 Qmax was the best predictors for the Total watershed (Figure 7, Table 6). SSYEV is calculated from Q so it is expected that Qsum correlated closely with SSYEV (Duvert et al., 2012; Rankl, 2004). Discharge metrics were highly correlated with SSYEV in the Total watershed, suggesting they 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 SSY is generated (Figure 7a).

<Table 6 here please>

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

In general, SSYEV\_TOTAL was higher than SSYEV\_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 event with much higher SSYEV at FG1 (Figure 7d) did not have corresponding data for FG2 or FG3, to determine if this event was data error. 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’alu, low rainfall can persist for several weeks, perhaps altering water and sediment dynamics in subsequent storm events.

<Figure 7 here please>

A higher intercept (α) for the human-disturbed compared to the undisturbed watershed indicates higher SSYEV for the same size storm event. A difference in slope (β) indicates the relative subwatershed contributions vary with storm size. 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 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 Qsum-SSYEV model indicates a decrease in relative contribution from the disturbed Lower watershed, but the Psum- and Qmax-SSYEV models show no change over increasing storm size (Figure 7). It was hypothesized that SSYEV from undisturbed forest would become the dominant source for larger storms, but the DR remains high for large storms due to naturally low SSYEV 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 SSY estimates varied, depending on which storm metric or set of storms (all, Table 2, Table 4) was used. The Qmax models (with bias correction) and Equation 6 using all events gave different annual SSY estimates at both the Upper watershed (41-129 tons/yr) and the Total watershed (655-428 tons/yr). The Psum model resulted in much lower estimates due to higher scatter about the Psum-SSYEV relationship for large events, even with bias correction, compared with the more robust Qmax-SSYEV model (Table 7). The Qmax-SSYEV model prediction is sensitive to the storm-size distribution, with significantly more SSYEV for events with higher Qmax. Comparing annual SSYestimates from different methods, using different sets of storm sizes can therefore make it appear that there is much disagreement when in fact this variability arises mostly from the variation in storm size distribution.

<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 method used here. All storms with measured SSYEV\_UPPER from 2012-2014 included 3,457 mm of precipitation (PEVmeas), or 125% of PEVann, so estimated annual SSYUPPER (Equation 6) was 41 tons/yr (45 tons/km²/yr). All storms with measured SSYEV\_TOTAL from 2012-2014 included 2,628 mm of precipitation, or 95% of expected annual storm precipitation so estimated annual SSYTOTAL was 428 tons/yr (241 tons/km²/yr).

## 5. Discussion

### 5.1 SSC and SSYEV for disturbed and undisturbed watersheds

#### 5.1.1 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 6a). 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 SSYEV with other kinds of sediment disturbance

SSY at Faga’alu was 3.9x higher than 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 SSY by two to three orders of magnitude in catchments of several km², exceeding yields from the most unstable, tectonically active natural environments of Southeast Asia (Douglas, 1996). 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 Great Barrier Reef (GBR) catchment (423,000 km2) where SSY increased by a factor of 5.5x since European settlement (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 a major sediment source in humid forested regions (Lewis et al., 2001; Ramos-Scharrón and Macdonald, 2005; Reid and Dunne, 1984), most roads in the urban area in Faga’alu 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.

Annual sSSY from the quarry was estimated from Equation 6 and sSSY from disturbed area in the Lower\_Quarry (Table 5) to be approximately 6,700 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 SSYEV with storm metrics

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). 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 in diverse watersheds.

In Faga'alu, SSYEV was least correlated with the EI. Rodrigues et al. (2013) hypothesized that EI 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 EI was more correlated with soil loss in an agricultural watershed than a forested watershed, and Faga'alu is mainly covered in dense forest. 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 SSYEV\_UPPER and Psum and EI. SSYLOWER was hypothesized to be generated by sheetwash and rill formation at the quarry and agricultural plots, whereas SSYUPPER 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.

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 Qmax-SSYEV 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. Most studies do not correct storm metric-SSY models for log-bias, as is suggested by Ferguson (1986) for Q-SSC relationships, so we calculated the bias correction factor separately from the intercept (Equation 5) to compare our model slopes and intercepts with these other studies. In five semi-arid to arid watersheds (2.1 - 1,538 km²) in Wyoming, United States, Qmax- SSYEV relationship intercepts ranged from 111 - 4,320 (Qmax in m³/s/km², SSYEV 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 0.4 and 2.4 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 under 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 1.41 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.

### 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 ~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 45-143 tons/km²/yr from the undisturbed Upper watershed, and 241-368 tons/km²/yr from the disturbed Total watershed (estimated from Qmax model with bias correction and Equation 6 with all events).

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. Their regional models of sSSY as a function of basin size and maximum elevation were not corrected for log-transform bias, but 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 (Table 8). 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 (uncorrected for l og-transform bias) 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.

SSY 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 (45-143 tons/km2/yr) but similar to the disturbed Lower (441-598 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 higher than the Total Faga’alu watershed (241-368 tons/km2/yr). Overall, both Hawaiian watersheds have higher SSY than Faga’alu, which is consistent with the low Qmax-SSYEV 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. The anthropogenic impact on SSYEV may vary by storm magnitude, as documented in Pacific Northwest forests (Lewis et al., 2001), but the storm metric models developed here showed contradictory results. 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.

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 and can be rapidly conducted if mitigation or disturbance activities are already planned.

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## References

Asselman, N.E.M., 2000. Fitting and interpretation of sediment rating curves. J. Hydrol. 234, 228–248. doi:10.1016/S0022-1694(00)00253-5

Basher, L., Hicks, D., Clapp, B., Hewitt, T., 2011. Sediment yield response to large storm events and forest harvesting, Motueka River, New Zealand. New Zeal. J. Mar. Freshw. Res. 45, 333–356. doi:10.1080/00288330.2011.570350

Basher, L.R., Hicks, D.M., Handyside, B., Ross, C.W., 1997. Erosion and sediment transport from the market gardening lands at Pukekohe, Auckland, New Zealand. J. Hydrol. 36, 73–95.

Bégin, C., Brooks, G., Larson, R. a., Dragićević, S., Ramos Scharrón, C.E., Coté, I.M., 2014. Increased sediment loads over coral reefs in Saint Lucia in relation to land use change in contributing watersheds. Ocean Coast. Manag. 95, 35–45. doi:10.1016/j.ocecoaman.2014.03.018

Blong, R.J., Humphreys, G.S., 1982. Erosion of road batters in Chim Shale, Papua New Guinea. Civ. Eng. Trans. Inst. Eng. Aust. CE24 1, 62–68.

Boning, C., 1992. Recommendations for use of retransformation methods in regression models used to estimate sediment loads (“The bias correction problem”).

Bonta, J. V, 2000. Impact of Coal Surface Mining and Reclamation on Suspended Sediment in Three Ohio Watersheds. JAWRA J. Am. Water Resour. Assoc. 36, 869–887.

Brunner, G., 2010. HEC-RAS River Analysis System.

Calhoun, R.S., Fletcher, C.H., 1999. Measured and predicted sediment yield from a subtropical, heavy rainfall, steep-sided river basin: Hanalei, Kauai, Hawaiian Islands. Geomorphology 30, 213–226.

Cox, C.A., Sarangi, A., Madramootoo, C.A., 2006. Effect of land management on runoff and soil losses from two small watersheds in St Lucia. L. Degrad. Dev. 17, 55–72. doi:10.1002/ldr.694

Craig, P., 2009. Natural History Guide to American Samoa. National Park of American Samoa, Pago Pago, American Samoa.

Dames & Moore, 1981. Hydrologic Investigation of Surface Water for Water Supply and Hydropower.

Douglas, I., 1996. The impact of land-use changes, especially logging, shifting cultivation, mining and urbanization on sediment yields in humid tropical Southeast Asia: A review with special reference to Borneo. IAHS-AISH Publ. 236, 463–471.

Duan, N., 2016. Smearing Estimate : A Nonparametric Retransformation Method Author ( s ): Naihua Duan Source : Journal of the American Statistical Association , Vol . 78 , No . 383 ( Sep ., 1983 ), pp . 605-610 Published by : Taylor & Francis , Ltd . on behalf of the Ame. J. Am. Stat. Assoc. 78, 605–610.

Duvert, C., Gratiot, N., 2010. Construction of the stage-discharge rating curve and the SSC-turbidity calibration curve in San Antonio Coapa 2009 hydrological season.

Duvert, C., Nord, G., Gratiot, N., Navratil, O., Nadal-Romero, E., Mathys, N., Némery, J., Regüés, D., García-Ruiz, J.M., Gallart, F., Esteves, M., 2012. Towards prediction of suspended sediment yield from peak discharge in small erodible mountainous catchments (0.45–22km2) of France, Mexico and Spain. J. Hydrol. 454-455, 42–55. doi:10.1016/j.jhydrol.2012.05.048

Fabricius, K.E., 2005. Effects of terrestrial runoff on the ecology of corals and coral reefs: review and synthesis. Mar. Pollut. Bull. 50, 125–46. doi:10.1016/j.marpolbul.2004.11.028

Fahey, B.D., Marden, M., 2000. Sediment yields from a forested and a pasture catchment, coastal Hawke’s Bay, North Island, New Zealand. J. Hydrol. 39, 49–63.

Fahey, B.D., Marden, M., Phillips, C.J., 2003. Sediment yields from plantation forestry and pastoral farming, coastal Hawke’s Bay, North Island, New Zealand. J. Hydrol. 42, 27–38.

Fallon, S.J., White, J. c., McCulloch, M.T., 2002. Porites corals as recorders of mining and environmental impacts : Misima Island , Papua New Guinea 66, 45–62.

Fenner, D., Speicher, M., Gulick, S., Aeby, G., Aletto, S.C., Anderson, P., Carroll, B.P., DiDonato, E.M., DiDonato, G.T., Farmer, V., Fenner, D., Gove, J., Gulick, S., Houk, P., Lundblad, E., Nadon, M., Riolo, F., Sabater, M.G., Schroeder, R., Smith, E., Speicher, M., Tuitele, C., Tagarino, A., Vaitautolu, S., Vaoli, E., Vargas-angel, B., Vroom, P., 2008. The State of Coral Reef Ecosystems of American Samoa, in: The State of Coral Reef Ecosystems of the United States and Pacific Freely Associated States. pp. 307–351.

Ferguson, R.I., 1986. River Loads Underestimated by Rating Curves. Water Resour. Res. 22, 74–76. doi:10.1029/WR022i001p00074

Ferguson, R.I., Grieve, I.C., Harrison, D.J., 1991. Disentangling land use effects on sediment yield from year to year climatic variability. Sediment Stream Water Qual. a Chang. Environ. Trends Explan. 203, 13–20.

Ferrier, K.L., Taylor Perron, J., Mukhopadhyay, S., Rosener, M., Stock, J.D., Huppert, K.L., Slosberg, M., 2013. Covariation of climate and long-term erosion rates across a steep rainfall gradient on the Hawaiian island of Kaua’i. Bull. Geol. Soc. Am. 125, 1146–1163. doi:10.1130/B30726.1

Fuka, D., Walter, M., Archibald, J., Steenhuis, T., Easton, Z., 2014. EcoHydRology.

Gellis, A.C., 2013. Factors influencing storm-generated suspended-sediment concentrations and loads in four basins of contrasting land use, humid-tropical Puerto Rico. Catena 104, 39–57. doi:10.1016/j.catena.2012.10.018

Gippel, C.J., 1995. Potential of turbidity monitoring for measuring the transport of suspended solids in streams. Hydrol. Process. 9, 83–97.

Gomi, T., Moore, R.D., Hassan, M.A., 2005. Suspended sediment dynamics in small forest streams of the Pacific Northwest. J. Am. Water Resour. Assoc.

Gray, a. B., Warrick, J. a., Pasternack, G.B., Watson, E.B., Go??i, M. a., 2014. Suspended sediment behavior in a coastal dry-summer subtropical catchment: Effects of hydrologic preconditions. Geomorphology 214, 485–501. doi:10.1016/j.geomorph.2014.03.009

Gray, J.R., 2014. Measuring Suspended Sediment, in: Ahuja, S. (Ed.), Comprehensive Water Quality and Purification. Elsevier, pp. 157–204. doi:10.1016/B978-0-12-382182-9.00012-8

Gray, J.R., Glysson, G.D., Turcios, L.M., Schwarz, G.E., 2000. Comparability of Suspended-Sediment Concentration and Total Suspended Solids Data U.S. Geological Survey Water-Resources Investigations Report 00-4191. Reston, Va.

Harmel, R.D., Cooper, R.J., Slade, R.M., Haney, R.L., Arnold, J.G., 2006. Cumulative uncertainty in measured streamflow and water quality data for small watersheds. Trans. Am. Soc. Agric. Biol. Eng. 49, 689–701.

Harmel, R.D., Smith, D.R., King, K.W., Slade, R.M., 2009. Estimating storm discharge and water quality data uncertainty: A software tool for monitoring and modeling applications. Environ. Model. Softw. 24, 832–842.

Harrelson, C.C., Rawlins, C.L., Potyondy, J.P., 1994. Stream channel reference sites: an illustrated guide to field technique. USDA Forest Service General Technical Report RM-245. US Department of Agriculture, Fort Collins, CO.

Henderson, G.W., Toews, D.A.A., 2001. Using Sediment Budgets to Test the Watershed Assessment Procedure in Southeastern British Columbia, in: Toews, D.A.A., Chatwin, S. (Eds.), Watershed Assessment in the Southern Interior of British Columbia. B.C. Ministry of Forests, Research Branch, Victoria, British Columbia, pp. 189–208.

Hettler, J., Irion, G., Lehmann, B., 1997. Environmental impact of mining waste disposal on a tropical lowland river system: a case study on the Ok Tedi Mine, Papua New Guinea. Miner. Depos. 32, 280–291. doi:10.1007/s001260050093

Hewlett, J.D., Hibbert, A.R., 1967. Factors affecting the response of small watershed to precipitation in humid areas. For. Hydrol. 275–279.

Hicks, D.M., 1990. Suspended sediment yields from pasture and exotic forest basins, in: Proceedings of the New-Zealand Hydrological Society Symposium. Auckland, New Zealand.

Hicks, D.M., Hoyle, J., Roulston, H., 2009. Analysis of sediment yields within Auckland region. ARC Technical Report 2009/064. Prepared by NIWA for Auckland Regional Council.

Holst-Rice, S., Messina, A., Biggs, T.W., Vargas-Angel, B., Whitall, D., 2015. Baseline Assessment of Fagaʻalu Watershed: A Ridge to Reef Assessment in Support of Sediment Reduction Activities. NOAA Coral Reef Conservation Program, Silver Spring, MD.

Horsley-Witten, 2011. American Samoa Erosion and Sediment Control Field Guide.

Horsley-Witten, 2012. Post-Construction Stormwater Training Memorandum.

Kearns, R., 2013. Personal Communication.

Kinnell, P.I.A., 2013. Modelling event soil losses using the Q R EI 30 index within RUSLE2. Hydrol. Process. doi:10.1002/hyp

Koch, R.W., Smillie, G.M., 1986. Comment on “ River Loads Underestimated by Rating Curves ” by R. I. Ferguson. Water Resour. Res. 22, 2121–2122.

Kostaschuk, R. a, Terry, J.P., Raj, R., 2002. Suspended sediment transport during tropical-cyclone floods in Fiji. Hydrol. Process. 17, 1149–1164.

Kroon, F.J., Kuhnert, P.M., Henderson, B.L., Wilkinson, S.N., Kinsey-Henderson, A., Abbott, B., Brodie, J.E., Turner, R.D.R., 2012. River loads of suspended solids, nitrogen, phosphorus and herbicides delivered to the Great Barrier Reef lagoon. Mar. Pollut. Bull. 65, 167–81. doi:10.1016/j.marpolbul.2011.10.018

Latinis, D.K., Moore, J., Kennedy, J., 1996. Archaeological Survey and Investigations Conducted at the Faga’alu Quarry, Ma'oputasi County, Tutuila, American Samoa, February 1996: Prepared for George Poysky, Sr., Samoa Maritime, PO Box 418, Pago Pago, American Samoa, 96799. Archaeological Consultants of the Pacific Inc., 59-624 Pupukea Rd., Haleiwa, HI 96712.

Lewis, J., 1996. Turbidity-controlled suspended sediment sampling for runoff-event load estimation. Water Resour. Res. 32, 2299–2310.

Lewis, J., Mori, S.R., Keppeler, E.T., Ziemer, R.R., 2001. Impacts of Logging on Storm Peak Flows , Flow Volumes and Suspended Sediment Loads in Caspar Creek, CA, in: Land Use and Watersheds: Human Influence on Hydrology and Geomorphology in Urban and Forest Areas. pp. 1–76.

McDougall, I., 1985. Age and Evolution of the Volcanoes of Tutuila American Samoa. Pacific Sci. 39, 311–320.

Megahan, W.F., 1980. Erosion from roadcuts in granitic slopes of the Idaho Batholith, in: Proceedings Cordilleran Sections of the Geological Society of America, 76th Annual Meeting. Oregon State University, Corvallis, OR, p. 120.

Megahan, W.F., Wilson, M., Monsen, S.B., 2001. Sediment production from granitic cutslopes on forest roads in Idaho, USA. Earth Surf. Process. Landforms 26, 153–163.

Milliman, J.D., Syvitski, J.P.M., 1992. Geomorphic/tectonic control of sediment discharge to the ocean: the importance of small mountainous rivers. J. Geol. 100, 525–544.

Minella, J.P.G., Merten, G.H., Reichert, J.M., Clarke, R.T., 2008. Estimating suspended sediment concentrations from turbidity measurements and the calibration problem. Hydrol. Process. 22, 1819–1830. doi:10.1002/hyp.6763

Nakamura, S., 1984. Soil Survey of American Samoa. US Department of Agriculture Soil Conservation Service, Pago Pago, American Samoa.

Nathan, R.J., McMahon, T. a, 1990. Evaluation of Automated Techniques for Base Flow and Recession Analyses. Water Resour. Res. 26, 1465–1473. doi:10.1029/WR026i007p01465

Nearing, M. a, Nichols, M.H., Stone, J.J., Renard, K.G., Simanton, J.R., 2007. Sediment yields from unit-source semiarid watersheds at Walnut Gulch. Water Resour. Res. 43, 1–10. doi:10.1029/2006WR005692

Perreault, J., 2010. Development of a Water Budget in a Tropical Setting Accounting for Mountain Front Recharge: Tutuila, American Samoa. University of Hawai’i.

Perroy, R.L., Bookhagen, B., Chadwick, O. a., Howarth, J.T., 2012. Holocene and Anthropocene Landscape Change: Arroyo Formation on Santa Cruz Island, California. Ann. Assoc. Am. Geogr. 102, 1229–1250. doi:10.1080/00045608.2012.715054

Ramos-Scharrón, C.E., Macdonald, L.H., 2005. Measurement and prediction of sediment production from unpaved roads, St John, US Virgin Islands. Earth Surf. Process. Landforms 30, 1283–1304.

Ramos-Scharrón, C.E., Macdonald, L.H., 2007. Measurement and prediction of natural and anthropogenic sediment sources, St. John, US Virgin Islands. Catena 71, 250–266.

Rankl, J.G., 2004. Relations Between Total-Sediment Load and Peak Discharge for Rainstorm Runoff on Five Ephemeral Streams in Wyoming. U.S. Geological Survey Water-Resources Investigations Report 02-4150. Denver, CO.

Rapp, A., 1960. Recent development of mountain slopes in Karkevagge and surroundings, northern Scandinavia. Geogr. Ann. 42, 65–200.

Reid, L.M., Dunne, T., 1984. Sediment production from forest road surfaces. Water Resour. Res. 20, 1753–1761.

Reid, L.M., Dunne, T., 1996. Rapid evaluation of sediment budgets. Catena Verlag, Reiskirchen, Germany.

Risk, M.J., 2014. Assessing the effects of sediments and nutrients on coral reefs. Curr. Opin. Environ. Sustain. 7, 108–117. doi:10.1016/j.cosust.2014.01.003

Rodrigues, J.O., Andrade, E.M., Ribeiro, L.A., 2013. Sediment loss in semiarid small watershed due to the land use. Rev. Ciência Agronômica 44, 488–498.

Rotmann, S., Thomas, S., 2012. Coral tissue thickness as a bioindicator of mine-related turbidity stress on coral reefs at Lihir Island, Papua New Guinea. Oceanography 25, 52–63.

Sadeghi, S.H.R., Mizuyama, T., Miyata, S., Gomi, T., Kosugi, K., Mizugaki, S., Onda, Y., 2007. Is MUSLE apt to small steeply reforested watershed? J. For. Res. 12, 270–277. doi:10.1007/s10310-007-0017-9

Slaymaker, O., 2003. The sediment budget as conceptual framework and management tool. Hydrobiologia 494, 71–82.

Stock, J.D., Rosener, M., Schmidt, K.M., Hanshaw, M.N., Brooks, B.A., Tribble, G., Jacobi, J., 2010. Sediment budget for a polluted Hawaiian reef using hillslope monitoring and process mapping, in: American Geophysical Union Fall Meeting. p. #EP22A–01.

Stock, J.D., Tribble, G., 2010. Erosion and sediment loads from two Hawaiian watersheds, in: 2nd Joint Federal Interagency Conference. Las Vegas, NV.

Storlazzi, C.D., Norris, B.K., Rosenberger, K.J., 2015. The influence of grain size, grain color, and suspended-sediment concentration on light attenuation: Why fine-grained terrestrial sediment is bad for coral reef ecosystems. Coral Reefs 34, 967–975. doi:10.1007/s00338-015-1268-0

Syvitski, J.P.M., Vörösmarty, C.J., Kettner, A.J., Green, P., 2005. Impact of humans on the flux of terrestrial sediment to the global coastal ocean. Science (80-. ). 308, 376–380. doi:10.1126/science.1109454

Thomas, S., Ridd, P. V, Day, G., 2003. Turbidity regimes over fringing coral reefs near a mining site at Lihir Island, Papua New Guinea. Mar. Pollut. Bull. 46, 1006–14. doi:10.1016/S0025-326X(03)00122-X

Tonkin & Taylor International Ltd., 1989. Hydropower feasibility studies interim report - Phase 1. Ref: 97/10163.

Topping, J., 1972. Errors of Observation and their Treatment, 4th ed. Chapman and Hall, London, UK.

Tropeano, D., 1991. High flow events, sediment transport in a small streams in the “Tertiary Basin” area in Piedmont (northwest Italy). Earth Surf. Process. Landforms 16, 323–339.

Turnipseed, D.P., Sauer, V.B., 2010. Discharge Measurements at Gaging Stations, in: U.S. Geological Survey Techniques and Methods Book 3, Chap. A8. Reston, Va., p. 87.

URS Company, 1978. American Samoa Water Resources Study: Assessment of Water Systems American Samoa. Coastal Zone Information Center, Honolulu, HI.

USGS, NRTWQ, 2016. Methods for Computing Water Quality Using Regression Analysis [WWW Document]. URL http://nrtwq.usgs.gov/md/methods/ (accessed 3.1.16).

Walling, D.E., 1977. Assessing the accuracy of suspended sediment rating curves for a small basin. Water Resour. Res. 13, 531–538.

Walling, D.E., 1999. Linking land use, erosion and sediment yields in river basins. Hydrobiologia 410, 223–240.

Walling, D.E., Collins, a. L., 2008. The catchment sediment budget as a management tool. Environ. Sci. Policy 11, 136–143. doi:10.1016/j.envsci.2007.10.004

Wemple, B.C., Jones, J.A., Grant, G.E., 1996. Channel Network Extension by Logging Roads in Two Basins, Western Cascades, Oregon. Water Resour. Bull. 32, 1195–1207.

Wolman, M.G., Schick, A.P., 1967. Effects of construction on fluvial sediment, urban and suburban areas of Maryland. Water Resour. Res. 3, 451–464.

Wong, M., 1996. Analysis of Streamflow Characteristics for Streams on the Island of Tutuila, American Samoa. U.S. Geological Survey Water-Resources Investigations Report 95-4185.

Wulf, H., Bookhagen, B., Scherler, D., 2012. Climatic and geologic controls on suspended sediment flux in the Sutlej River Valley, western Himalaya. Hydrol. Earth Syst. Sci. 16, 2193–2217. doi:10.5194/hess-16-2193-2012

Zimmermann, A., Francke, T., Elsenbeer, H., 2012. Forests and erosion: Insights from a study of suspended-sediment dynamics in an overland flow-prone rainforest catchment. J. Hydrol. 170–181.

## APPENDIX A. Dams in Faga'alu watershed

Faga'alu stream was dammed at 4 locations above the village: 1) Matafao Dam (elevation 244 m) near the base of Mt. Matafao, draining 0.20 km², 2) Vaitanoa Dam at Virgin Falls (elevation 140 m), draining an additional 0.44 km², 3) a small unnamed dam below Vaitanoa Dam at elevation 100m, and 4) Lower Faga'alu Dam (elevation 48 m), immediately upstream of a large waterfall 30 m upstream of the quarry, draining an additional 0.26 km² (Tonkin & Taylor International Ltd., 1989). A 2012 aerial LiDAR survey (Photo Science, Inc.) indicates the drainage area at the Lower Faga'alu Dam is 0.90 km². A small stream capture/reservoir (~35 m³) is also present on a side tributary that joins Faga'alu stream on the south bank, opposite the quarry. It is connected to a ~6 cm diameter pipe but it is unknown when or by whom it was built, its initial capacity, or if it is still conveying water. During all site visits water was overtopping this small structure through the spillway crest, suggesting it is fed by a perennial stream.

Matafao Dam was constructed in 1917 for water supply to the Pago Pago Navy base, impounding a reservoir with initial capacity of 1.7 million gallons (6,400 m³) and piping the flow out of the watershed to a hydropower and water filtration plant in Fagatogo. In the early 1940's the Navy replaced the original cement tube pipeline and hydropower house with cast iron pipe but it is unknown when the scheme fell out of use (Tonkin & Taylor International Ltd., 1989; URS Company, 1978). Remote sensing and a site visit on 6/21/13 confirmed the reservoir is still filling to the spillway crest with water and routing some flow to the Fagatogo site, though the amount is much less than the 10 in. diameter pipes conveyance capacity and the flow rate variability is unknown. A previous site visit on 2/21/13 by American Samoa Power Authority (ASPA) found the reservoir empty of water but filled with an estimated 3-5 meters of fine sediment (Kearns, 2013). Interviews with local maintenance staff and historical photos confirmed the Matafao Reservoir was actively maintained and cleaned of sediment until the early 70's.

The Vaitanoa (Virgin Falls) Dam, was built in 1964 to provide drinking water but the pipe was not completed as of 10/19/89, and a stockpile of some 40 (8 ft. length) 8 in. diameter asbestos-cement pipes was found on the streambanks. Local quarry staff recall the pipes were removed from the site sometime in the 1990's. The Vaitanoa Reservoir had a design volume of 4.5 million gallons (17,000m³), but is assumed to be full of sediment since the drainage valves were never opened and the reservoir was overtopping the spillway as of 10/18/89 (Tonkin & Taylor International Ltd., 1989). A low masonry weir was also constructed downstream of the Vaitanoa Dam, but not connected to any piping.

The Lower Faga'alu Dam was constructed in 1966/67 just above the Samoa Maritime, Ltd. Quarry, as a source of water for the LBJ Medical Centre. It is unknown when this dam went out of use but in 1989 the 8 in. conveyance pipe was badly leaking and presumed out of service. The 8 in. pipe disappears below the floor of the Samoa Maritime quarry and it is unknown if it is still conveying water or has plugged with sediment. The derelict filtration plant at the entrance to the quarry was disconnected prior to 1989 (Tonkin & Taylor International Ltd., 1989). The original capacity was 0.03 million gallons (114 m³) but is now full of coarse sediment up to the spillway crest. No reports were found indicating this structure was ever emptied of sediment.

## APPENDIX B. Stream gaging in Faga’alu Watershed

Stream gaging sites were chosen to take advantage of an existing control structure at FG1 (Figure B.1) and a stabilized stream cross section at FG3 (Figure B.2)(Duvert and Gratiot, 2010). At FG1 and FG3, Q was calculated from 15 minute interval stream stage measurements, using a stage-Q rating curve calibrated to manual Q measurements made under baseflow and stormflow conditions (Figures B.3 and B.4). Stream stage was measured with non-vented pressure transducers (PT) (Solinst Levelogger or Onset HOBO Water Level Logger) installed in stilling wells at FG1 and FG3. Barometric pressure data collected at Wx were used to calculate stage from the pressure data recorded by the PT. Data gaps in barometric pressure from Wx were filled by data from stations at Pago Pago Harbor (NSTP6) and NOAA Climate Observatory at Tula (TULA) (Figure 1). Priority was given to the station closest to the watershed with valid barometric pressure data. Barometric data were highly correlated and the data source made little (<1cm) difference in the resulting water level. Q was measured in the field by the area-velocity method (AV) using a Marsh-McBirney flowmeter to measure flow velocity and channel surveys measure cross-sectional area (Harrelson et al., 1994; Turnipseed and Sauer, 2010).

AV-Q measurements could not be made at high stages at FG1 and FG3 for safety reasons, so stage-Q relationships were constructed to estimate a continuous record of Q. At FG3, the channel is rectangular with stabilized rip-rap on the banks and bed (Figure B.2). Recorded stage varied from 4 to 147 cm. AV-Q measurements (n= 14) were made from 30 to 1,558.0 L/sec, covering a range of stages from 6 to 39 cm. The highest recorded stage was much higher than the highest stage with measured Q so the rating could not be extrapolated by a power law. Stream conditions at FG3 fit the assumption for Manning's equation, so the stage-Q rating at FG3 was created using Manning's equation, calibrating Manning's n (0.067) to the Q measurements (Figure B.3).

At FG1, the flow control structure is a masonry ogee spillway crest of a defunct stream capture. The structure is a rectangular channel 43 cm deep that transitions abruptly to gently sloping banks, causing an abrupt change in the stage-Q relationship (Figure B.1). At FG1, recorded stage height ranged from 4 to 120 cm, while area-velocity Q measurements (n= 22) covered stages from 6 to 17 cm. Since the highest recorded stage (120 cm) was higher than the highest stage with measured Q (17 cm), and there was a distinct change in channel geometry above 43 cm the rating could not be extrapolated by a power law. The flow structure did not meet the assumptions for using Manning's equation to predict flow so the HEC-RAS model was used (Brunner, 2010). The surveyed geometry of the upstream channel and flow structure at FG1 were input to HEC-RAS, and the HEC-RAS model was calibrated to the Q measurements (Figure B.4). While a power function fit Q measurements better than HEC-RAS for low flow, HEC-RAS fit better for Q above the storm threshold used in analyses of SSY (Figure B.4).

## APPENDIX C. Water discharge during storm events

<Table C.1 here please>

## APPENDIX D. Turbidity-Suspended Sediment Concentration rating curves for turbidimeters in Faga'alu

Turbidity (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. Storm events with incomplete or invalid T data were not used in the analysis. A three-point calibration was performed on the YSI turbidimeter with YSI turbidity standards (0, 126, and 1000 NTU) at the beginning of each field season and approximately every 3-6 months during data collection. Turbidity measured with 0, 126, and 1000 NTU standards differed by less than 10% (4-8%) during each recalibration. The OBS requires calibration every two years, so recalibration was not needed during the study period. All turbidimeters were cleaned following storms to ensure proper operation.

At FG3, a YSI turbidimeter recorded T (NTU) at 5 min intervals from January 30, 2012, to February 20, 2012, and at 15 min intervals from February 27, 2012 to May 23, 2012, when it was damaged during a large storm. The YSI turbidimeter was replaced with an OBS, which recorded Backscatter (BS) and Sidescatter (SS) at 5 min intervals from March 7, 2013, to July 15, 2014 (OBSa), and was resampled to 15 min intervals. No data was recorded from August 2013-January 2014 when the wiper clogged with sediment. A new OBS was installed at FG3 from January, 2014, to August, 2014 (OBSb). To correct for some periods of high noise observed in the BS and SS data recorded by the OBSa in 2013, the OBSb installed in 2014 was programmed to make a burst of 100 BS and SS measurements at 15 min intervals, and record Median, Mean, STD, Min, and Max. All BS and SS parameters were analyzed to determine which showed the best relationship with SSC. Mean SS showed the highest r2 and is a physically comparable measurement to NTU measured by the YSI and TS (Anderson, 2005).

At FG1, the TS turbidimeter recorded T (NTU) at 5 min intervals from January 2012 until it was vandalized and destroyed in July 2012. The YSI turbidimeter, previously deployed at FG3 in 2012, was repaired and redeployed at FG1 and recorded T (NTU) at 5 min intervals from June 2013 to October 2013, and January 2014 to August 2014. T data was resampled to 15 min intervals to compare with SSC samples for the T-SSC relationship, and to correspond to Q for calculating SSY.

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 T-SSC relationship was developed for each turbidimeter, at each location, using 15 min interval T data and SSC samples from storm periods only (Figure D.1). A "synthetic" T-SSC relationship was also developed by placing the turbidimeter in a black tub with water, and sampling T and SSC as sediment was added (Figure D.2), but results were not comparable to T-SSC relationships developed under actual storm conditions (Minella et al., 2008) and were not used in further analyses.

The T-SSC relationships varied among sampling sites and sensors but all showed acceptable r2 values (0.79-0.99). Lower scatter was achieved by using grab samples collected during stormflows only. For the TS (not shown) and YSI deployed at FG1, the r2 values were high (0.58, 0.99) but the ranges of T and SSC values used to develop the relationships were considered too small (0-16 NTU) for the TS compared to the maximum observed during the deployment period (1,077 NTU) to develop a robust relationship for higher T values. Instead, the T-SSC relationship developed for the YSI turbidimeter installed at FG1 (Figure D.1a-b, dotted line) was used to calculate SSC from T data collected by the TS and the YSI at FG1. For the YSI turbidimeter, more scatter was observed in the T-SSC relationship at FG3 than at FG1 (Figure D.1a-b), which could be attributed to the higher number and wider range of values sampled, and to temporal variability in sediment characteristics. The OBSa and OBSb turbidimeters had high r2 values (0.82, 0.93) and compared well between the two periods of deployment (Figure D.1c-d).