# 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 yields (SSY) were measured during storm and non-storm periods 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 suspended sediment concentration (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 1.7-3.9x 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 SSYEV 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 sediment yield increased significantly (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 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 load and restore coral reefs.

## Keywords:

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; West and van Woesik, 2001). 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. 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. In the Caribbean, unpaved roads covering 0.3-0.9% of the watershed area were the dominant sediment source in disturbed watersheds on St. John, 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.

Management of sediment 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, challenging 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 SSYEV from small, mountainous catchments is a significant contribution for establishing baselines for change-detection for sediment mitigation projects, and can also further improve models applied at the regional scale (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. 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), stream discharge (Q), turbidity (T) and suspended sediment concentration (SSC) to accomplish two objectives: 1) quantify suspended sediment yield from undisturbed and human-disturbed portions of a small watershed in the south Pacific and 2) develop an empirical model of storm-generated suspended sediment yield. The research questions are: How much has human disturbance increased suspended sediment yield to the coast? What human activities dominate the anthropogenic contribution to the suspended sediment load? Which storm metric is the best predictor of storm event suspended sediment yield (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?

## 2. Study Area

The study watershed, Faga'alu, is located on Tutuila (14S, 170W), the largest island in the Territory of American Samoa (140 km²). Like many volcanic islands in the Pacific, Tutuila has steep, heavily forested mountains with villages and roads mostly confined to the flat areas near the coast. The main stream in Faga'alu runs the length of the watershed (~3 km), and drains an area of 1.78 km² into Faga'alu Bay (area draining to FG3 in Figure 1). The main watershed includes Matafao Mountain, the highest point on Tutuila (653 m). The mean slope of the main Faga'alu watershed is 0.53 m/m and total relief is 653 m. The administrative boundary 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). The coral reef in Faga’alu Bay is highly degraded by sediment (Fenner et al., 2008). Faga'alu watershed was identified by local environmental management agencies in the American Samoa Coral Reef Advisory Group (CRAG) as a heavily impacted watershed, and in August 2012 was selected by the US Coral Reef Task Force (USCRTF) as a Priority Watershed for conservation and remediation efforts (Holst-Rice et al., 2015).

Faga’alu occurs on intracaldera Pago Volcanics where the K-Ar age for a sample in the watershed is 1.20 Mya (McDougall, 1985). Soil types in the steep uplands are Fagasa family-lithic hapludolls with rock outcrops in the steep uplands, and soil types in the lowlands are Aua-Leafu complex (Nakamura, 1984). In the uplands, an estimated 50% of soil cover is Fagasa family soils which are moderately deep and well drained silty clay (50-150 cm) overlying weathered igneous bedrock. An estimated 20% of soil cover is lithic hapludolls which are well drained but shallower (10-50 cm) than Fagasa family soil, and composed of silty clay and clay loam. The remaining 15% of soil in the uplands is rock outcrops. The lowlands are composed of urban surfaces and a mix of Aua and Leafu soils, composed of colluvium and alluvium derived from the weathered igneous rock and soil from the steep uplands. Aua soils in the lowlands are deep (>150 cm), well drained accumulations of very stony silty clay loam with only moderate runoff and erosion potential. Leafu soils in the lowlands are very deep (>150 cm), poorly drained silty clay to fine sandy loam that are typically along streams and valley bottoms where the high water table is typically 90-150 cm deep.

### 2.1 Climate

Precipitation on Tutuila is caused by several mechanisms including cyclones and tropical depressions, isolated thunderstorms, and orographic uplifting of trade-wind squalls over the high (300-600 m), mountainous ridge that runs the length of the island. The ridge runs parallel to the predominant wind direction, and does not cause a significant windward/leeward rainfall gradient like many other Pacific Islands (Ferrier et al., 2013; Menking et al., 2013). Average annual specific discharge (m3/yr/km2) shows little spatial variation across the island, irrespective of watershed location or orientation (Dames & Moore, 1981). Precipitation increases with elevation, from an average 2,380 mm/yr at the shoreline to 6,350 mm/yr at the highest elevation on the island, averaging 3,800 mm/yr over the island from 1903 to 1973 (Eyre, 1989; Izuka et al., 2005). In Faga'alu watershed, rainfall records show average annual precipitation 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). Mean annual potential evapotranspiration follows the opposite trend, varying from 890 mm/yr at high elevation to 1,150 mm/yr at sea level (Izuka et al., 2005). Tropical cyclones are erratic but occurred on average every 1-13 years from 1981-2014 (Craig, 2009) and bring intense rainfall, flooding, landslides, and high sediment yield (Buchanan-Banks, 1979).

There are two subtle rainfall seasons: a drier winter season, from June through September and a wetter summer season, from October through May (Izuka et al., 2005). During the drier winter season, the island is influenced by relatively stronger, predominantly east to southeast trade winds, lower temperatures, lower humidity and lower total rainfall. During the wetter summer season the Inter-Tropical Convergence Zone (ITCZ) moves over the region, causing light to moderate Northerly winds, higher temperatures, higher humidity, and higher total rainfall. While total rainfall is lower in the drier tradewind season, large storm events are still observed. Analysis of 212 peak discharges at 11 continuous-record gaging sites 1959-1990 showed 65% of annual peak flows occurred during the wet season and 35% of annual peak flows occurred during the drier Tradewind season (Wong, 1996). Analysis of mean monthly rainfall data for the period 1971-2000 showed that 75% of precipitation occurred in the wet season, which includes 67% of the year (October-May), and 25% occurred in the dry season, which covers 33% of the year (June-September) (Perreault, 2010; data from USGS rain gauges and Parameter-elevation Relationships on Independent Slopes Model (PRISM) Climate Group (Daly et al., 2008)).

### 2.2 Land Cover and Land Use

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), based on a 1 m2-resolution land cover map from NOAA’s Ocean Service and Coastal Services Center (2010). 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. This settlement pattern is typical in the South Pacific and other volcanic islands, where their small size and steep topography constrain development to valley bottoms near the coast (Bégin et al., 2014). Compared to other watersheds on Tutuila, a relatively large portion of Faga'alu watershed is urbanized (3.2% "High Intensity Developed" in Table 1), due to large areas of impervious surface associated with the hospital and the numerous residences and businesses. A small portion of the 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. Farmers of these plots receive technical assistance from the Natural Resource Conservation Service (NRCS) to mitigate erosion. 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). Longitudinal sampling of Faga'alu stream during low flow conditions in 2011 showed significantly increased turbidity downstream of a bridge construction site on the village road approximately 200 m downstream of FG2 (Curtis et al., 2011). Construction of the bridge was completed in March 2012 and no longer increases turbidity.

An open-pit aggregate quarry covers 1.6 ha and accounts for the majority of the bare land, which covers 1.1% of the Faga'alu watershed (Table 1). The quarry has been in continuous operation since the 1960's by advancing into the steep hillside to quarry the underlying basalt formation (Latinis et al., 1996). The overburden of soil and weathered rock was either piled up on-site where it was eroded by storms, or was manually rinsed from crushed aggregate. With few sediment runoff controls in place, sediment was discharged directly to Faga'alu stream. In 2011, the quarry operators installed some sediment runoff management practices such as silt fences and 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 naturally overgrown by vegetation (Figure 2), altering the sediment availability. In late 2014, large sediment retention ponds were installed to mitigate sediment runoff and work is underway to document the reduction in sediment loading (Messina and Biggs, forthcoming; See Holst-Rice et al. (2015) for a full description of sediment mitigation efforts at the quarry).

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 only the highest, Matafao Reservoir, was ever connected to the municipal water system and has since fallen out of use (Tonkin & Taylor International Ltd., 1989) (Figure 1). The dam at point FG1 has filled with bedload sediment and flows over the spillway even at the lowest flows. 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 suspended sediment yield (SSY) in Faga'alu stream was measured at three sampling points that drain key land covers we hypothesized would have different SSY: FG1 drains undisturbed forest in the UPPER subwatershed (watershed boundary to FG1), FG2 drains undisturbed forest and the quarry in the LOWER\_QUARRY subwatershed (between FG1 and FG2), and FG3 drains undisturbed forest and the village in the LOWER\_VILLAGE subwatershed (between FG2 and FG3) (Table 1). FG3 is also the watershed outlet for the TOTAL watershed.

### 3.1 Calculating suspended sediment yield from individual storm events (SSYEV)

SSYEV at FG1, FG2, and FG3 were calculated 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 (10-6). | | |

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). Dunne and Leopold (1978) assert that all hydrograph separation schemes are arbitrary and usually have little to do with the processes that generate storm flow, but if a consistent method is used then at least the results of different analyses can be compared. Graphical techniques may be implemented to separate the hydrograph into baseflow and quickflow, using the start and end of quickflow as the start and end of the storm event (Dunne and Leopold, 1978; Perreault, 2010). Storms can also be filtered from the analysis by using various criteria such as minimum storm duration, time between discharge peaks, minimum peak discharge, or more complex schemes using statistical distributions of flow percentiles (Gellis, 2013; Lewis et al., 2001). More complex signal processing methods can also be used, including finding the inflection point of the second derivative of the hydrograph to determine the end of the storm event. However, complex events occur where subsequent precipitation generates stormflow before the stream has returned to baseflow. In these cases, the storm definition scheme can significantly affect the analysis of storm sediment yields by separating or combining multiple hydrograph peaks. Due to the high number of storm events and the prevalence of complex storm events recorded at the study site, an automated approach that robustly separated complex events was desirable. The storm definition approach used in this study performed baseflow separation with a digital filter signal processing technique (Nathan and McMahon, 1990) embedded in the R-statistical package EcoHydRology (Fuka et al., 2014). Only events with quickflow for at least one hour and peak flow greater than 10% of baseflow were included in the analysis. This approach was easily automated for application to a large number of events, and adequately separated complex storm events with multiple hydrograph peaks (See Appendix C for example).

### 3.2 Field Data Collection

Data on precipitation (P), water discharge (Q), suspended sediment concentration (SSC) and turbidity (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.

#### 3.2.1 Precipitation

Precipitation (P) was measured at three locations in Faga'alu watershed using Rainwise RAINEW tipping-bucket rain gages (RG1 and RG2) and a Vantage Pro Weather Station (Wx) (Figure 1). Data at RG2 was only recorded January-March, 2012, to determine a relationship between elevation and precipitation in the LOWER subwatershed. While previous data suggest that precipitation increases with elevation (Izuka et al., 2005), here we do not calculate watershed-mean precipitation, and instead use precipitation depth at RG1 to indicate the depth of rainfall during a storm event. Most sheetwash and rill erosion, which depends on rainfall intensity and erosivity, occurred at the quarry, near the location of RG1. Rainfall data from RG1 is therefore most representative of rainfall at the quarry. The total event precipitation (Psum) and event Erosivity Index (EI30) were calculated using data from RG1, with data gaps filled by 15 min interval precipitation data from Wx.

#### 3.2.2 Water Discharge

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 taken at 15 minute intervals and a stage-Q rating curve calibrated to manual Q measurements. Q was measured in the field under both baseflow and stormflow conditions by the area-velocity method (AV) using a Marsh-McBirney flowmeter to measure flow velocity and channel surveys of cross-sectional area (Harrelson et al., 1994; Turnipseed and Sauer, 2010). The highest recorded stage was higher than the highest stage with 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 ogee spillway crest of a defunct stream capture. Since the highest recorded stage (120 cm) was higher than the highest stage with measured Q (17 cm), and the flow structure did not meet the assumptions for using Manning's equation to predict flow, 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.

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). This assumes that specific water discharge from the subwatershed above FG2 is similar to above FG1. Discharge may be higher from the quarry surface, which represents 5.7% of the LOWER\_QUARRY subwatershed, so Q, and thus SSY from the quarry are a conservative, lower bound estimate, 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.

#### 3.2.3 Continuous Suspended Sediment Concentration

Continuous SSC at 15 minute intervals was estimated from 1) linear interpolation of SSC measured from water samples, and 2) 15 min interval turbidity data (T) 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. 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 could only be 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).

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 (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 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.

#### 3.2.4 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:

|  |  |  |
| --- | --- | --- |
|  |  | 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 (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.

### 3.3 Relationship of sediment load to sediment budget

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). 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.

### 3.4 Quantifying SSY from disturbed and undisturbed subwatersheds

A main objective for this study was to quantify anthropogenic changes in SSY EV\_TOTAL as measured at FG3. Relative contributions to SSY EV\_TOTAL from undisturbed and human-disturbed areas were assessed using two approaches: 1) comparing SSYEV contributions from subwatersheds for each storm and the average of all storms, and 2) the Disturbance Ratio (DR).

The percent contributions of subwatersheds to SSY EV\_TOTAL were calculated from SSYEV measured at FG1, FG2, and FG3 (Figure 1). SSYEV from the UPPER subwatershed was measured at FG1 (SSYEV\_UPPER = SSYEV\_FG1). SSYEV from the LOWER subwatershed was calculated as SSYEV\_LOWER=SSYEV\_FG3-SSYEV\_FG1. Where SSYEV data at FG2 were also available, the contributions from the quarry subwatershed (SSYEV\_LOWER\_QUARRY = SSYEV\_FG2-SSYEV\_FG1), and village subwatershed (SSYEV\_LOWER\_VILLAGE = SSYEV\_FG3-SSYEV\_FG2) were calculated separately.

Land cover in the LOWER subwatershed includes both undisturbed and human-disturbed surfaces. To calculate SSYEV from disturbed areas, SSYEV from undisturbed areas was estimated using the specific SSYEV (sSSYEV tons/km²) from the UPPER subwatershed multiplied by the undisturbed area in the LOWER subwatershed:

|  |  |  |
| --- | --- | --- |
|  |  | Equation 3 |
| where *SSYEV\_distrb* is SSYEV from disturbed areas only (tons), *SSYEV\_subws* is SSYEV (tons) measured from the disturbed 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 disturbed subwatershed (km2). | | |

The disturbance ratio (DR) is the ratio of SSYEV from the watershed under current conditions to SSYEV under pre-disturbance conditions, estimated using sSSYUPPER:

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

Both Equation 3 and 4 assume that the whole watershed was originally covered in forest, and sSSYEV from forested areas in the LOWER subwatershed equals sSSYEV from the undisturbed UPPER watershed. SSYEV from the disturbed portions of the LOWER subwatershed (Equation 3) was used to calculate a DR for just the disturbed areas in the LOWER subwatershed.

### 3.5 Predicting event suspended sediment yield (SSYEV)

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). SSYEV and the discharge metrics (Qsum and Qmax) were normalized by watershed area to compare different sized watersheds.

The relationship between SSYEV and storm metrics is often best fit by a power law function:

|  |  |  |
| --- | --- | --- |
|  |  | 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. | | |

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 undisturbed areas. A difference in slope (β) would indicate the relative sediment contributions from the subwatersheds change with increasing storm size. If regression slopes for the UPPER and TOTAL watersheds are significantly different, it supports the conclusion that the effect of human-disturbance changes with storm size.

### 3.6 Annual estimates of SSY and sSSY

Annual estimates of SSY and sSSY were calculated to compare Faga'alu with other watersheds reported in the literature. 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 turbidimeters 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 (unpublished data), so the Qmax-SSYEV relationship developed prior to the mitigation was used to calculate the annual pre-mitigation sediment yield. For storms with no 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 (Psann) to the precipitation measured during storms where SSYEV was measured (Psmeas):

|  |  |  |
| --- | --- | --- |
|  |  | Equation 6 |
| where *SSYann* is estimated annual SSY from storms, *SSYEV\_meas* is SSYEV from sampled storms (all, Tables 2 and 4), PEV\_meas is precipitation measured during the sampled storms, and PEV\_annis 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 and Q observed between storms.

## 4. Results

### 4.1 Field Data Collection

#### 4.1.1 Precipitation

Annual precipitation measured at RG1, with gaps filled with data from Wx, 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). No difference in measured P was found between RG1 and Wx, or between RG1 and RG2, so P was assumed to be homogenous over the watershed for all analyses. 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 precipitation 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). Precipitation data measured at higher elevations would be useful to determine a more robust orographic precipitation relationship. For this analysis, however, the absolute values of total precipitation in each subwatershed are not as important since precipitation and the erosivity index are only used as predictive storm metrics.

#### 4.1.2 Water Discharge

Discharge at both FG1 and FG3 was characterized by periods of low but perennial baseflow, punctuated by short, flashy hydrograph peaks (FG1: max 8,356 L/sec, FG3: max 13,071 L/sec) (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).

#### 4.1.3 Storm Events

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. 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 events at FG1, and 74 events at FG3. Of those storms, 42 events had data for P, Q, and SSC at both FG1 and FG3 to calculate SSYEV from the LOWER subwatershed. 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.

Most storm events showed a typical pattern, where a short period of intense rainfall caused a rapid increase in SSC downstream of the quarry (FG2) while SSC remained low at the undisturbed forest site (FG1) (Figure 4). The highest SSC was typically observed at FG2, with slightly lower and later peak SSC observed at FG3. SSC downstream of the undisturbed forest (FG1) typically increased more slowly, remained lower, and peaked later than the disturbed sites downstream of the quarry (FG2) and the village (FG3). Though peak SSC was highest at FG2, the highest SSY was measured at FG3 due to the addition of storm runoff and sediment from the larger subwatershed draining to FG3.

#### 4.1.4 Suspended Sediment Concentration

From January 6, 2012, to October 1, 2014, 506 water samples were collected at FG1 (n=59), FG2 (n=90 grab samples, n=198 from the Autosampler), and FG3 (n=159). Mean (μ) and maximum SSC of water samples, collected during non-stormflow and stormflow periods by grab and autosampler, were lowest at FG1 (μ=28 mg/L, max=500 mg/L), highest at FG2 (μ=337 mg/L, max=12,600 mg/L), and in between at FG3 (μ=148 mg/L, max=3,500 mg/L). At FG1, 24% of grab samples (n=14) were collected during non-stormflow, μ=8 mg/L (Figure 5a); 76% of grab samples (n=45) were collected during stormflow, μ= 35 mg/L (Figure 8b). At FG2, 23% of grab samples (n=21) were collected during non-stormflow, μ= 105 mg/L; 77% of grab samples (n=69) were collected during stormflow, μ= 409 mg/L. At FG3, 25% of samples (n=39) were collected during non-stormflow, μ= 52 mg/L; 75% of samples (n=120) were collected during stormflow, μ= 179 mg/L. This pattern of SSC values suggests that little sediment is contributed from the forest upstream of FG1, followed by a large input of sediment between FG1 and FG2, and then SSC is diluted by addition of stormflow with lower SSC between FG2 and FG3.

Probability plots of the SSC data collected at FG1, FG2 and FG3 showed they were highly non-normal, so non-parametric tests for statistical significance were applied. The results of the Kruskall-Wallis test were significant for non-stormflow (p<10-4) and stormflow (p<10-4); means of SSC samples were significantly different among all three locations. The results of the pair-wise Mann-Whitney test between FG1 and FG2 were significant (non-stormflow, p<10-4; stormflow, p<10-4), but between FG2 and FG3 were significant for non-stormflow (p<0.05) but not for stormflow (p>0.10); means of SSC samples at FG1 and FG2 were significantly different, but FG2 and FG3 were not.

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 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 sampled downstream of the undisturbed forest, 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.).

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, 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 (Q\_FG3=287 L/sec) (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.

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 then discharged directly into the stream, causing high SSC during baseflow periods with no precipitation 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 during storm events.

#### 4.1.5 Cumulative Probable Error (PE)

Cumulative Probable Error (RMSE %) for SSYEV estimates at FG1 and FG3 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 Comparing SSYEV from disturbed and undisturbed subwatersheds

SSYEV was measured simultaneously at FG1 and FG3 for 42 storms (Table 2). SSYEV\_TOTAL was 129.2±121.4 tons (72.6±68.2 tons/km²), with 17.0±7.3 tons (18.8±8.1 tons/km²) from the UPPER subwatershed and 112.2 tons (127.5 tons/km²) from the LOWER subwatershed. The UPPER and LOWER subwatersheds are similar in size (0.90 km² and 0.88 km²) but SSYEV\_UPPER accounted for an average of just 13% and SSYEV\_LOWER for 87% of SSYEV at the watershed outlet (Table 2). The DR estimated from sSSYEV\_UPPER (=18.8 tons/km²) and sSSYEV\_LOWER (Equation 4) suggests sSSYEV has increased by 6.8x in the LOWER subwatershed, and 3.9x for the TOTAL watershed.

SSYEV from the undisturbed forest areas in the LOWER watershed was estimated to be 14.9 tons for the 42 events in Table 2 (Equation 3), so SSYEV from the disturbed areas was 97.3 tons (Table 3). Approximately 87% of SSYEV\_LOWER was from disturbed areas, despite the disturbed areas only accounting for 10.1% of the LOWER subwatershed area (0.089 km²). Similarly, despite only 5.2% of the TOTAL watershed being disturbed, 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.

It was hypothesized the quarry was a key sediment source, but SSYEV was measured simultaneously at FG1, FG2, and FG3 for only 8 of the storms in Table 2. SSYEV was calculated separately from the LOWER subwatershed containing the quarry (SSYEV\_LOWER\_QUARRY) and LOWER subwatershed containing the village below the quarry (SSY EV\_LOWER\_VILLAGE) for those 8 storms (Table 4). For the 8 storms in Table 4, SSY EV\_TOTAL was 46 tons with an average of 29% 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 results from the smaller sample of storms in Table 4, show a slightly lower increase in SSY from the TOTAL watershed, 1.7x, but show the sSSY has increased by 4.08x in the LOWER\_QUARRY subwatershed and 1.8x in the LOWER\_VILLAGE subwatershed.

Very 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, despite only 5.2% of the TOTAL watershed being disturbed, 75-45% of SSY EV\_TOTAL was from disturbed areas (Tables 3 and 5). Bare land in the LOWER\_QUARRY subwatershed significantly increased sSSYLOWER\_QUARRY and sSSYTOTAL, and contributed the majority of SSY from disturbed areas in Faga'alu watershed. sSSY from disturbed areas in the UPPER (37.0 tons/km²), LOWER\_QUARRY (721.6 tons/km²), and LOWER\_VILLAGE subwatersheds (116.2 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.

### 4.3 Predicting SSYEV from storm metrics

SSYEV from the UPPER and TOTAL watersheds was correlated with each of the four storm metrics tested (Figure 7), though the correlations with precipitation metrics were poor in the heavily forested UPPER watershed (Table 6). Pearson and Spearman correlation coefficients were similar, meaning the relationships were mostly linear in log-log space. Significant scatter was observed around all models, which reflects the changing sediment availability at the quarry and village, and the natural variability in the watershed response for different storm events.

Qsum was the best predictor of SSYEV for the UPPER watershed, and Psum was the best predictor for the TOTAL watershed, though Qmax was nearly as good a predictor for both watersheds. SSYEV is calculated from Q so it is expected that Qsum should correlate closely with SSYEV, as observed in other studies (Duvert et al., 2012; Rankl, 2004). Indeed the Qsum model for the UPPER watershed showed the highest coefficient of determination (r²), lowest RMSE, and highest Pearson and Spearman correlation coefficients (Table 6). Psum showed an equally high r² and a lower RMSE, but only for the TOTAL subwatershed. This suggests that sediment production is more related to discharge processes in the UPPER subwatershed, and more related to precipitation processes in the LOWER subwatershed. Discharge metrics were also highly correlated with SSYEV in the TOTAL watershed, suggesting discharge metrics are good predictors in both disturbed and undisturbed watersheds. Qmax was not the best predictor in either watershed, but performed well in both watersheds, with similar correlation statistics to both Qsum and Psum models. 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.

Precipitation was measured at the quarry, which may reflect precipitation characteristics more accurately in the LOWER than the UPPER watershed. 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.

In all models, 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. These events could be attributed to measurement error or to landslides in the UPPER subwatershed and the increased sediment supply for that specific event. 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 model intercepts (α) were significantly different (p<0.01), but only the Qsum-SSYEV model showed significantly different (p<0.01) slopes (β). 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).

The relative contribution 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 natural 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 Annual estimates of SSY and sSSY

Estimates of annual sSSY depended on which predictor was used to estimate SSYEV. Annual sSSY from the UPPER and TOTAL watersheds was 14 tons/km²/yr and 75 tons/km²/yr, respectively, as predicted by Psum-SSYEV relationship, and 68 tons/km²/yr and 247 tons/km²/yr, respectively using the Qmax-SSYEV relationship (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. These results suggest the UPPER watershed contributed 14%, and the LOWER subwatershed contributed 86% of annual SSY from the TOTAL watershed.

In order to compare with SSY estimated from the Psum-SSYEV and Qmax-SSYEV relationships, annual SSY was also calculated 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. Continuous records of Q and precipitation in 2014 showed annual storm precipitation (Psann) was 2,770 mm, representing 69% of total annual precipitation (3,709 mm). All storms with measured SSYEV at FG1 from 2012-2014 included 3,457 mm of precipitation (Psmeas), or 125% of Psann, 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). These results suggest the UPPER watershed contributed 10%, and the LOWER subwatershed contributed 90% of annual SSY from the TOTAL watershed.

For storms with measured SSYEV at both FG1 and FG3 (Table 2), PEVmeas was 1,004 mm, or 36% of PEVann. From Equation 6, annual SSY increased from the UPPER (46 tons/yr), LOWER (310 tons/yr), and TOTAL watershed (360 tons/yr). Annual sSSY increased from the UPPER (51 tons/km2/yr), LOWER (350 tons/km2/yr), and TOTAL watershed (200 tons/km²/yr), and, respectively.

For storms with measured SSYEV at FG1, FG2, and FG3 (Table 4), PEVmeas was 299 mm, or 11% of PEVann. Annual SSY increased from the UPPER (120 tons/yr), LOWER\_QUARRY subwatershed (150 tons/yr), LOWER\_VILLAGE subwatershed (150 tons/yr), LOWER subwatershed (300 tons/yr), and TOTAL watershed (420 tons/yr). Annual sSSY increased from the UPPER (140 tons/km²/yr), LOWER\_QUARRY (560 tons/km²/yr), LOWER\_VILLAGE (250 tons/km²/yr), LOWER (340 tons/km²/yr), and TOTAL watershed 240 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 Methods for quantifying human impact

Event-wise measurement of SSYEV allowed rapid quantification of sediment loading from natural and human-disturbed areas. Event wise analysis was useful because hysteresis and interstorm variability caused significant scatter in the instantaneous Q-SSC relationship. 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 of sediment loading, which complicated detection of human impact on sediment concentrations and yield. Measurement of SSYEV allows comparison of similar size storms to determine change over space and time without problems of interannual variability in precipitation totals, and the simple regression models that predict annual sediment load from either precipitation or stormflow measurements eliminate the need for long-term field work to estimate annual total yields. From a management perspective, the event-wise approach to estimating human impacts on sediment is less expensive than efforts to measure annual yields since it does not require a full year of monitoring and can be rapidly conducted if mitigation or disturbance activities are already planned. With predictive models of SSYEV that are based on an easily-monitored storm metric like maximum event discharge, SSYEV can be modeled in the future to compare with either post-mitigation or post-disturbance SSYEV.

The estimation of human impact on sediment loads was facilitated by the spatial arrangement of disturbances and by the lack of significant sediment storage in the watershed. In Faga'alu watershed, and other similar steep watersheds, human-disturbance is often constrained to the lower watershed, and sediment yields from these key sources can be measured separately from the undisturbed forest upstream. Reid and Dunne (1996) argue that in cases where there is a clear management question and the study area can be divided into sub-units, a sediment budget can be rapidly developed with only a few field measurements and limited periods of field monitoring. The use of event-wise sampling in subwatersheds with specific land uses allowed for separation of different sources to the sediment budget.

### 5.2 Interpreting slope and intercept of the Qmax-SSYEV relationship

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. Duvert et al. (2012) found that intercepts of the Qmax-SSYEV relationship are also dependent on the regression fitting method. 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 Faga'alu watersheds, respectively, which 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 . 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 Comparing sSSY and SSC in other small Pacific Island watersheds

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). The scatter around their model is large for smaller watersheds, and the Faga’alu data fall within the range of scatter (Figures 5e and 6e in Milliman and Syvitski (1992)).

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 the observation 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 Faga’alu (mean 148 mg/L, maximum 3,500 mg/L). 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. These values are all higher than observed at Faga’alu under both undisturbed (45-68 tons/km2/yr) and 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 as 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.

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. Literature values show measured sSSY from cutslopes varying 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

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 similar increases in total SSY to coral environments. 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 watershed, 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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## 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

Insert Table C.1 here

## 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 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) 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 FG3 (Figure D.1a) 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), 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.1b).