# Introduction

Anthropogenic watershed disturbance by industry, agriculture, deforestation, roads, and urbanization alters the timing, composition, and mass of sediment loads to coral reefs, causing enhanced sediment stress on corals near the outlets of impacted watersheds (Syvitski et al., 2005; West and van Woesik, 2001). Anthropogenic sediment disturbance may be exacerbated on volcanic, tropical islands characterized by high rainfall, extreme weather events, steep slopes, erodible soils, and naturally dense vegetation, where land clearing alters the fraction of exposed soil much more than in regions with sparse vegetation. On Molokai, Stock et al. (2010) found that less than 5% of the land produces most of the sediment, and of that 5%, only 1% produces ~50% of the sediment, concluding that management should focus on identifying, quantifying, and mediating erosion hotspots (Risk, 2014). However, knowledge of fluvial suspended sediment yield (SSY) on most Pacific volcanic islands remains limited due to the challenges of in situ monitoring, and existing sediment yield models are not well-calibrated to the climatic, topographic, and geologic conditions found on steep, tropical islands (Calhoun and Fletcher, 1999). Developing models that predict SSY from small, mountainous catchments is a significant contribution for local coral conservation, and can also further improve models applied at the regional scale (Duvert et al., 2012).

Traditional approaches to quantifying human impact on sediment yield, including comparison of total annual yields (Fahey et al., 2003) and sediment rating curves (Asselman, 2000; Walling, 1977), are complicated by interannual variability and hysteresis in the discharge-concentration relationship. As an alternative, recent studies (Basher et al., 2011; Duvert et al., 2012) have compared SSY generated by storm events of the same magnitude to detect human impacts and develop empirical models. SSY generated by individual storm events (SSYEV) may correlate with various precipitation and discharge variables (“storm metrics”), including total precipitation, the Erosivity Index, total discharge, or maximum event discharge (Qmax), but the best correlation has consistently been found with Qmax. Qmax integrates the whole hydrological response of a watershed, making it a good predictor variable 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 SSY may vary by storm magnitude, as documented in Mediterranean climates (White and Greer, 2006) and in Pacific Northwest forests (Lewis et al., 2001). As storm magnitude increases, water yield and/or SSY from natural areas may increase relative to human-disturbed areas, diminishing anthropogenic impact. While large storms account for most SSY in natural conditions, human-disturbed areas may show the most significant disturbance for smaller storms (Lewis et al., 2001). It is hypothesized that the disturbance ratio (DR) is highest for small storms, when background SSY from the undisturbed forest is low and erodible sediment from disturbed surfaces in the lower watershed is the dominant source. For large storms, it is hypothesized mass movements and bank erosion contribute to naturally high SSY from the undisturbed upper watershed, reducing the DR for large events.

This study uses in situ measurements of precipitation, stream discharge, and suspended sediment concentration to quantify sediment yield from key areas of the watershed and develop an empirical model of storm-generated sediment yield to a priority coral reef. The questions addressed include: How has human disturbance increased sediment loading to Faga’alu Bay? How do sediment contributions from human-disturbed areas and undisturbed areas vary with storm size? And Which is the best predictor of storm event suspended sediment yield (SSYEV): total precipitation, Erosivity Index, total discharge, or maximum event discharge?

# Study Area

Precipitation on Tutuila (14 S, 170 W) is caused by major storms including cyclones and tropical depressions, isolated thunderstorms, and orographic uplifting of trade-wind squalls over the high (300-600m), mountainous ridge that runs the length of the island. Unlike many other Pacific Islands, the mountainous ridge runs parallel to the predominant wind direction, and does not cause a significant windward/leeward rainfall gradient. There are two subtle rainfall seasons—a drier season, from June to September (32% of annual P) and a wetter season, from October to May (68% of annual P). During the wetter summer season the Inter-Tropical Convergence Zone (ITCZ) moves over the island, causing relatively light Northerly winds, higher temperatures, higher humidity, and higher rainfall. During the drier winter season, the island is influenced by the southeast Trades and relatively stronger, predominantly East to Southeast winds, lower temperatures, lower humidity and lower rainfall.

Long-term rain gage records show a strong precipitation gradient with increasing elevation. Rainfall records from 1903-1973 show average precipitation is 6,350 mm at Matafao Mtn. (653m m.a.s.l), 5,280mm at Matafao Reservoir (249m m.a.s.l.) and about 3,800mm on the coastal plain (Craig, 2009; Dames & Moore, 1981; Tonkin & Taylor International Ltd., 1989; Wong, 1996)(). Potential evapotranspiration follows the opposite trend, with annual mean PET varying from 890mm at high elevation to 1,150mm at sea level (Izuka, 2005). Precipitation varies orographically from an average 6,350mm/yr at high elevation to 2,380mm/yr at the shoreline, averaging 3,800mm/yr over the island from 1903 to 1973 (Eyre, 1994). Tropical cyclones are erratic but recently have occurred on average every 1–13 years (Craig, 2009) and bring intense rainfall, flooding, landslides, and high sediment loading events (Buchanan-Banks, 1979). Analysis of 212 peak discharges at 11 continuous-record gaging sites up to 1990 showed 65.5% of annual peak flows occurred during the wet season (Wong, 1996). When controlling for drainage area, average annual specific discharge shows little spatial variation across the island, irrespective of location or orientation (Dames & Moore, 1981).

Faga’alu watershed (1.86 km2) is characterized by large areas of undisturbed, steeply sloping, heavily forested hillsides in the upper watershed, and similarly steep topography with relatively small flat areas that are urbanized or densely settled in the lower watershed (Figure 1). This settlement pattern is typical for volcanic islands with steep topography in the south Pacific. Monitoring efforts focused on Faga’alu, which discharges to a sediment-impacted reef (Aeby et al., 2006), and includes two unique features not found in “typical” watersheds in American Samoa: 1) an open aggregate quarry, and 2) a large impervious area associated with a hospital. Three water impoundment structures were built in the upper Faga’alu 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).

Land use in Faga’alu watershed includes agriculture, roads, and urbanization (Table 1). The predominant land cover in the Faga’alu watershed is undisturbed forest on the steep hillsides (85.7%). These forests are prone to natural landslides that can contribute large amounts of sediment during storm events (Buchanan-Banks, 1979; Calhoun and Fletcher, 1999). Compared to other watersheds on Tutuila, a relatively large portion of Faga’alu watershed is urbanized (“high intensity developed in Table 1, 4.6%), due to large areas of impervious surface associated with the hospital and the numerous residences and businesses. A small portion of the watershed (1.1%) is developed open space, which includes landscaped lawns and parks. In addition to some small, household gardens there are several small agricultural areas growing banana and taro on the steep hillsides. NOAA Land Cover map (2.5m res.) classified the agricultural plots as “Grassland” due to the high grass cover in the plots (Table 1) (NOAA’s Ocean Service and Coastal Services Center, 2010). These plots are currently receiving technical assistance from the Natural Resource Conservation Service (NRCS) to mitigate erosion problems.

In Faga’alu there is an open-pit aggregate quarry (~2ha) that accounts for the majority of the 1.1% bare land area in 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 1996](#_ENREF_8)). The quarry operators have installed some sediment management practices such as silt fences and settling ponds (Horsley-Witten, 2011) but they are unmaintained and likely inadequate to control the large amount of sediment mobilized by the intense tropical rains (Horsley-Witten, 2012a). Longitudinal sampling of Faga’alu stream in 2011 showed significantly increased turbidity downstream of the quarry and of a new bridge construction site on the village road (Curtis et al., 2011). Construction of the bridge was completed March 2012 and no longer increases turbidity. There are several small footpaths and unpaved driveways, but most unpaved roads are stabilized with compacted gravel and do not appear to be a major contributor of sediment (Horsley-Witten, 2012b).

# Methods

A nested-watershed approach was used to quantify the contribution of SSY from undisturbed and human-disturbed areas to total sediment loading to Faga’alu Bay during baseflow, and during storm events of varying magnitude. While steep, mountainous streams can discharge large amounts of bedload (Milliman and Syvitski, 1992), this research is focused on sediment size fractions that can be transported in suspension in the marine environment to settle on corals, and this is generally restricted to silt and clay fractions (<16um) (Asselman, 2000).

Predicting event suspended sediment yield (SSYEV)

SSY generated by individual storm events (SSYEV) can be used to compare the responses of different watersheds (Basher et al., 2011; Duvert et al., 2012; Fahey et al., 2003; Hicks, 1990), assess the contribution of individual subwatersheds to total SSY (Zimmermann et al., 2012), and determine changes in SSY from the same watershed over time (Bonta, 2000). SSYEV is calculated by integrating continuous suspended sediment load from measured or modeled discharge (Q) and suspended sediment concentration (SSC) (Duvert et al., 2012):

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|  |  | Equation 1 |
| where *SSYEV* is suspended sediment yield (tons) from t=0=storm start to T=storm end, *SSC* is suspended sediment concentration (mg/L), and *Q* is discharge (L/sec). | | |

SSYEV may be correlated with precipitation or discharge variables (“storm metrics”), so four storm metrics were tested in this research: total event precipitation (Psum), EI30 rainfall erosivity (EI30) (Hicks, 1990), total event discharge (Qsum), and peak event discharge (Qmax) (Duvert et al., 2012; Rodrigues et al., 2013). Storm metrics may be linearly or nonlinearly correlated with SSYEV, so both Pearson’s and Spearman’s correlation coefficients were calculated to select the best predictor of SSYEV from the total watershed, and from each subwatershed.

The relationship between SSYEV and storm metrics may be a linear function, but is often best fit by a watershed-specific power law function of the form:

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|  |  | Equation 2 |
| 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), normalized for watershed area. Linear functions were fit to untransformed (Linear) and log-transformed dependent and independent variables (Power Law), and best fit determined by coefficients of determination (r2). | | |

Disturbance Ratio

To assess the contribution of each subwatershed to total SSY from the watershed, the percent contribution of each subwatershed will be calculated as the difference between SSYEV observed at the upstream and downstream monitoring stations. Another approach is the disturbance ratio (DR), which is the ratio of SSYEV from the total human-disturbed watershed under current conditions (measured at the watershed outlet: VILLAGE and N1) to SSY under pre-disturbance conditions (SSYpre):

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|  |  | Equation 3 |

SSYpre is calculated assuming that the specific SSY from forested parts of the lower watershed is similar to the specific SSY from the upper watershed:

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|  |  | Equation 4 |

The percent contribution and DR will be calculated for each storm and averaged to determine the contribution of each subwatershed to total SSY.

Data Collection

Precipitation

Precipitation (P) was measured with Rainwise RAINEW tipping-bucket rain gages at 1 min intervals at three locations in Faga’alu watershed (Figure 3). Data at RG2 was only recorded January-March, 2012, to determine a relationship between elevation and precipitation. Precipitation at 15 min intervals was also measured at the Vantage Pro Weather Station (Wx) and used to fill any data gaps in the precipitation recorded at RG1. The event total precipitation (Psum) and EI30 for storm events were calculated using data from RG1, with data gaps filled by data from Wx.

Discharge

Stream discharge (Q) was derived from 15 min interval stream stage measurements, using a stage-discharge rating curve calibrated to Q measurements made under baseflow and stormflow conditions. Stream stage was measured with non-vented pressure transducers (PT) (Solinst Levelogger or Onset HOBO Water Level Logger) installed at two locations in Faga’alu: FOREST and VILLAGE. Stream gauging sites were chosen to take advantage of existing control structures (FOREST) or stabilized streambed and banks (VILLAGE). Barometric pressure data to calculate stage from PT’s was collected at Wx. Data gaps were filled by barometric data from stations at Pago Pago Harbor (NSTP6), Tafuna International Airport (TAFUNA), and NOAA Climate Observatory at Tula (TULA). Priority was given to station that was closest to the watershed with valid barometric pressure data.

Discharge (Q) was measured in the field by the area-velocity method (AV) using a Marsh-McBirney flowmeter to measure flow velocity and channel surveys to measure stream cross-section geometry (Harrelson et al., 1994; Turnipseed and Sauer, 2010). AV measurements were made at FOREST and VILLAGE in Faga’alu, and linear, log-linear, and nonlinear rating curves were tested for best fit. AV measurements could not be made at high stages at FOREST and VILLAGE for safety reasons, so the rating curve at FOREST was modeled with HEC-RAS (Brunner, 2010) and calibrated to the AV measurements. Manning’s equation was used to extend the rating curve at VILLAGE.

Suspended Sediment Discharge

Suspended sediment concentration (SSC) at 15 min intervals was derived from turbidity (T) measurements, using a T-SSC relationship calibrated to stream water samples collected over a range of Q and SSC. The T-SSC relationship is unique to each region, or even each stream, and can be influenced by water color, dissolved solids and organic matter, temperature, and the shape, size and composition of sediment particles. However, T has proved to be a robust surrogate measure of SSC in streams ([Gippel 1995](#_ENREF_3)) and is widely used for remote monitoring applications ([Lewis 1996](#_ENREF_8)).

Turbidity (T) was measured at 5 min intervals at FOREST and VILLAGE. Turbidity was measured at VILLAGE using a YSI 600OMS sonde with 6136 Turbidity Probe from February 2012 until it was damaged in May 2012. As a replacement, a CampbellSci OBS500 was then deployed at VILLAGE in March 2013 to March 2014, but no data was recorded from August 2013 –January 2014 due to instrument malfunction. A new CampbellSci OBS500 was installed at VILLAGE from January to August, 2014. Turbidity was measured at FOREST using a Greenspan TS3000 turbidimeter from January 2012 to July 2012 when it was vandalized and destroyed. The YSI turbidimeter previously deployed at VILLAGE was repaired and redeployed at FOREST June 2013 to October 2013, and January 2014 to August 2014. Turbidity of grab samples was also measured in the laboratory by a LaMotte 20/20 turbidimeter (LAB) to compare to T measured in the field. Turbidity data was resampled to 15 min intervals corresponding to Q for calculating suspended sediment yield (SSY) (Equation 1).

The VILLAGE-YSI rating was used to convert turbidity from all instruments to SSC, due to its good fit over the full range of SSC samples

Stream water samples for SSC were collected by dip sampling with 500mL HDPE bottles at FOREST, QUARRY, and VILLAGE, and by ISCO 3700 Autosamplers at QUARRY. Other sites were sampled opportunistically during storm events. From January 6, 2012, to February 26, 2014, 610 samples were collected at 12 sites in Faga’alu and analyzed for SSC. Samples were analyzed in the field using gravimetric methods (Gray et al., 2000). Water samples were vacuum filtered on 47mm, 0.7um Millipore AP40 glass fiber filters, oven dried at 100˚C for one hour, cooled and weighed to determine SSC (mg/L). Three main sampling locations in Faga’alu are the focus in this analysis: 1) Upstream (FOREST)(n=55), 2) immediately downstream of the Quarry (QUARRY)(n=247), and 3) Downstream (VILLAGE)(n=155).

Measurement Uncertainty

Uncertainty in SSYEV estimates arises from both measurement and model errors, including models of stage-discharge (stage-Q) and turbidity-suspended sediment concentration (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 estimate (Topping, 1972). The resulting cumulative probable error (uncertainty) is the square root of the sum of the squares of the maximum values of the separate errors:

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|  |  | Equation 5 |
| where PE is the cumulative probable error for individual measured values (±%), EQmeas = uncertainty in Q measurements (±%), ESSCmeas = uncertainty in SSC measurements (± %), EQmod = uncertainty in Q modeled by the Stage-Q relationship (RMSE, as ±% of the mean observed Q), ESSCmod = uncertainty in SSC modeled by the T-SSC relationship (RMSE, as ± % of the mean observed SSC)(Harmel et al., 2009). | | |

PE was calculated for each storm event to add a statistical measure of uncertainty to SSYEV (±tons). The effect of uncertain SSYEV estimates may complicate conclusions about SSYEV-Qmax relationships, contributions from subwatersheds, and anthropogenic impacts. This is common in sediment yield studies where successful models estimate SSY with ±50-100% accuracy (Duvert et al., 2012), but preliminary data suggested the difference in SSYEV from the upper and lower subwatersheds was significantly larger than the uncertainty in the SSY estimates.

# Results

Here are some great results!

# Discussion

They’re great results because…

# Conclusion

So we conclude that…