1   TITLE:

2   Contributions of human activities to suspended sediment yield during storm events

3   from a small, steep, tropical watershed

4   Authors:

5   Messina, A.M.[a*], Biggs, T.W.[a]

6   [a] San Diego State University, Department of Geography, San Diego, CA 92182,

7   amessina@rohan.sdsu.edu, +1-619-594-5437, tbiggs@mail.sdsu.edu, +1-619-594-0902

8   ABSTRACT

9   Suspended sediment yields (SSY) were measured during storm and non-storm periods from

10 undisturbed and human-disturbed portions of a small (1.8 km²), mountainous watershed that

11 drains to a sediment-stressed coral reef. Event-wise SSY (SSY_{EV}) was calculated for 142 storms

12 from measurements of water discharge (Q), turbidity (T), and suspended sediment concentration

13 (SSC) measured downstream of three key sediment sources: undisturbed forest, an aggregate

14 quarry, and a village. SSC and SSY_{EV} were significantly higher downstream of the quarry during

15 both storm- and non-storm periods. The human-disturbed subwatershed accounted for an average

16 of 71-87% of SSY_{EV} from the total watershed, and has increased loads to the coast by 1.7-3.9x

17 over natural background. Specific SSY (tons/area) from the disturbed quarry area was 49x higher

18 than from natural forest compared with 8x higher from the village. The quarry, which covers

19 1.1% of the total watershed area, contributed 36% of total SSY_{EV} at the outlet. Similar to

20 mountainous watersheds in semi-arid and temperate climates, SSY_{EV} from both the undisturbed

21 and disturbed watersheds correlated closely with maximum event discharge (Qmax), event total

22 precipitation and event total Q, but not with a precipitation erosivity index. Best estimates of

23   annual SSY_{EV} varied from 41-61 tons/yr (45-68 tons/km²/yr) from the undisturbed subwatershed,

24   310-388 tons/yr (350-441 tons/km²/yr) from the human-disturbed subwatershed, and 360-439

25   tons/yr (200-247 tons/km²/yr) from the total watershed. Sediment yield was very sensitive to

26   disturbance; only 5.2% of the watershed is disturbed by humans but sediment yield increased

27   significantly (3.9x). While unpaved roads are often identified as a source of sediment in humid

28   forested regions, field observations suggested that most roads in the urban area were stabilized

29   with aggregate. Repeated surface disturbance at the quarry is a key process maintaining high

30   rates of sediment generation. Given the large distance to other sources of building material,

31   aggregate mining and associated sediment disturbance may be a critical sediment source on

32   remote islands in the Pacific and elsewhere. Identification of sediment hotspots like the quarry

33   using rapid, event-wise measures of suspended sediment yield will help efforts to mitigate

34   sediment load and restore coral reefs.

38   Introduction

39   Human activities including deforestation, agriculture, road construction, mining, and

40   urbanization alter the timing, composition, and amount of sediment loads to downstream

41   ecosystems (Syvitski et al., 2005). Increased sediment loads can stress aquatic ecosystems,

42   including coral reefs that occur near the outlets of impacted watersheds. Sediment impacts coral

43   by decreasing light for photosynthesis and increasing sediment accumulation rates (Fabricius,

44   2005; Storlazzi et al., 2015; West and van Woesik, 2001). Anthropogenic sediment disturbance

45   can be particularly high on volcanic islands in the humid tropics, which have a high potential for

46   erosion due to high rainfall, extreme weather events, steep slopes, and erodible soils. Sediment

47   yield in densely vegetated watersheds can be particularly sensitive to land clearing, which alters

48   the fraction of exposed soil more than in sparsely-vegetated regions. The steep topography and

49   small floodplains on small volcanic islands further limits sediment storage and the capacity of

50   the watershed to buffer increased hillslope sediment supply. Such environments characterize

51   many volcanic islands in the south Pacific where coral reefs are impacted by sediment.

52   A large proportion of a watershed's sediment yield can originate from disturbed areas that

53   cover a relatively small fraction of the watershed area. In the Caribbean, unpaved roads covering

54   0.3-0.9% of the watershed area were the dominant sediment source in disturbed watersheds on

55   St. John, and increased sediment yield to the coast by 5-9 times relative to undisturbed

56   watersheds (Ramos-Scharrón and Macdonald, 2007). In the Pacific Northwest of the United

57   States, several studies found most road-generated sediment can originate from just a small

58   fraction of unpaved roads (Gomi et al., 2005; Henderson and Toews, 2001; Megahan et al., 2001;

59   Wemple et al., 1996), and heavily used roads could generate 130 times as much sediment as

60   abandoned roads (Reid and Dunne, 1984). In a watershed disturbed by grazing on Molokai,

61   Hawaii, less than 5% of the land produces most of the sediment, and only 1% produces

62   approximately 50% of the sediment (Risk, 2014; Stock et al., 2010), suggesting that management

63   should focus on identifying, quantifying, and mediating erosion hotspots.

64   Management of sediment requires linking land use changes and mitigation strategies to

65   changes in sediment yields at the watershed outlet (Walling and Collins, 2008). A sediment

66   budget quantifies sediment as it moves from key sources like hillslope erosion, channel-bank

67   erosion, and mass movements, to its eventual exit from a watershed (Rapp, 1960). Walling

68   (1999) used a sediment budget to show that sediment yield from watersheds can be insensitive to

69   both land use change and erosion management due to high sediment storage capacity on

70   hillslopes and in the channel. Sediment yield from disturbed areas can be large but may not be

71   important compared to naturally high yields from undisturbed areas. While a full description of

72   all sediment production and transport processes are of scientific interest, the sediment budget

73   needs to be simplified to be used as a management tool (Slaymaker, 2003). Most management

74   applications require only that the order of magnitude or the relative importance of process rates

75   be known, so Reid and Dunne (1996) argue a management-focused sediment budget can be

76   developed quickly in situations where the management problem is clearly defined and the

77   management area can be divided into homogenous sub-units.

78   Knowledge of suspended sediment yield (SSY) under both natural and disturbed

79   conditions on most tropical, volcanic islands remains limited, due to the challenges of in situ

80   monitoring in these remote, challenging environments. The limited data has also made it difficult

81   to develop reliable sediment yield models for ungauged watersheds. Existing sediment yield

82   models are often designed for agricultural landscapes and are not well-calibrated to the climatic,

83   topographic, and geologic conditions found on steep, tropical islands. Most readily available

84   models also do not incorporate many of the important processes that generate sediment in steep

85   watersheds, including mass movements (Calhoun and Fletcher, 1999; Ramos-Scharrón and

86   Macdonald, 2005; Sadeghi et al., 2007). Developing models that predict SSY_{EV} from small,

87   mountainous catchments is a significant contribution for establishing baselines for change-

88   detection for sediment mitigation projects, and can also further improve models applied at the

89   regional scale (Duvert et al., 2012).

90   Traditional approaches to quantifying human impact on sediment budgets, including

91   comparison of total annual yields (Fahey et al., 2003) and sediment rating curves (Asselman,

92   2000; Walling, 1977), are complicated by interannual climatic variability and hysteresis in the

93   discharge-concentration relationship. Sediment yield can be highly variable over various time

94   scales, even under natural conditions. At geologic time scales, if an undisturbed watershed is not

95   in a steady-state condition, sediment yields may decrease over time as it reaches equilibrium, or

96   the sediment contributions from different subwatersheds may change with time (Ferrier et al.,

97   2013; Perroy et al., 2012). At decadal scales, cyclical climatic variability like El Nino-Southern

98   Oscillation (ENSO) events or Pacific Decadal Oscillation (PDO) patterns can significantly alter

99   sediment yield from undisturbed watersheds (Wulf et al., 2012).

100   As an alternative to comparing annual sediment loads, SSY generated by storm events of

101   the same magnitude can be compared to assess the contribution of individual subwatersheds to

102   total SSY (Zimmermann et al., 2012), determine changes in SSY from the same watershed over

103   time (Bonta, 2000), and compare the responses of different watersheds to various precipitation or

104   discharge variables ("storm metrics") (Basher et al., 2011; Duvert et al., 2012; Fahey et al., 2003;

105   Hicks, 1990). Event-wise SSY (SSY_{EV}) may correlate with storm metrics such as total

106   precipitation, the Erosivity Index (Kinnell, 2013), or total discharge, but the best correlation has

107   consistently been found with maximum event discharge (Qmax). Several researchers have

108   hypothesized that Qmax integrates the hydrological response of a watershed, making it a good

109   predictor of SSY_{EV} in diverse environments (Duvert et al., 2012; Rankl, 2004). High correlation

110   between SSY_{EV} and Qmax has been found in semi-arid, temperate, and sub-humid watersheds in

111   Wyoming (Rankl, 2004), Mexico, Italy, France (Duvert et al., 2012), and New Zealand (Basher

112 et al., 2011; Hicks, 1990), but this approach has not been attempted for steep, tropical watersheds

113 on volcanic islands.

114   The anthropogenic impact on SSY_{EV} may vary by storm magnitude, as documented in

115 Pacific Northwest forests (Lewis et al., 2001). As storm magnitude increases, water yield and/or

116 SSY_{EV} from natural areas may increase relative to human-disturbed areas, diminishing

117 anthropogenic impact relative to the natural baseline. While large storms account for most SSY

118 under undisturbed conditions, human-disturbed areas may show the largest disturbance,

119 expressed as a percentage increase above the natural background, for smaller storms (Lewis et

120 al., 2001). The disturbance ratio (DR) may be highest for small storms, when background SSY_{EV}

121 from the undisturbed forest is low and erodible sediment from disturbed surfaces is the dominant

122 source. For large storms, mass movements and bank erosion may contribute to naturally high

123 SSY_{EV} from undisturbed watersheds, increasing the background and reducing the DR for large

124 events.

125   This study uses in situ measurements of precipitation (P), stream discharge (Q), turbidity

126 (T) and suspended sediment concentration (SSC) to 1) quantify suspended sediment yield from

127 undisturbed and human-disturbed portions of a small watershed in the south Pacific and 2)

128 develop an empirical model of storm-generated suspended sediment yield. The questions

129 addressed include: How much has human disturbance increased suspended sediment yield to the

130 coast? What human activities dominate the anthropogenic contribution to the suspended

131 sediment load? Which storm metric is the best predictor of storm event suspended sediment yield

132 (SSY_{EV}): total event precipitation, Erosivity Index, total event discharge, or maximum event

133 discharge? How do sediment contributions from undisturbed areas and human-disturbed areas

134 vary with storm size?

6

Study Area

136   The study watershed, Faga'alu, is located on Tutuila (14S, 170W), the largest island in

137   the Territory of American Samoa (140 km²). Like many volcanic islands in the Pacific, Tutuila

138   has steep, heavily forested mountains with villages and roads mostly confined to the flat areas

139   near the coast. The main stream in Faga'alu runs the length of the watershed (~3 km), and drains

140   an area of 1.78 km² into Faga'alu Bay (area draining to FG3 in Figure 1). The main watershed

141   includes Matafao Mountain, the highest point on Tutuila (653 m). The mean slope of the main

142   Faga'alu watershed is 0.53 m/m and total relief is 653 m. The administrative boundary includes

143   the watersheds of the main stream and several small ephemeral streams that drain directly to the

144   bay (0.63 km²) (grey dotted boundary in Figure 1). The coral reef in Faga'alu Bay is highly

145   degraded by sediment (Fenner et al., 2008). Faga'alu watershed was identified by local

146   environmental management agencies in the American Samoa Coral Reef Advisory Group

147   (CRAG) as a heavily impacted watershed, and in August 2012 was selected by the US Coral

148   Reef Task Force (USCRTF) as a Priority Watershed for conservation and remediation efforts

149   (Holst-Rice et al., 2015).

150   Faga'alu occurs on intracaldera Pago Volcanics where the K-Ar age for a sample in the

151   watershed is 1.20 Mya (McDougall, 1985). Soil types in the steep uplands are Fagasa family-

152   lithic hapludolls with rock outcrops in the steep uplands, and soil types in the lowlands are Aua-

153   Leafu complex (Nakamura, 1984). In the uplands, an estimated 50% of soil cover is Fagasa

154   family soils which are moderately deep and well drained silty clay (50-150 cm) overlying

155   weathered igneous bedrock. An estimated 20% of soil cover is lithic hapludolls which are well

156   drained but shallower (10-50 cm) than Fagasa family soil, and composed of silty clay and clay

157   loam. The remaining 15% of soil in the uplands is rock outcrops. The lowlands are composed of

158 urban surfaces and a mix of Aua and Leafu soils, composed of colluvium and alluvium derived

159 from the weathered igneous rock and soil from the steep uplands. Aua soils in the lowlands are

160 deep (>150 cm), well drained accumulations of very stony silty clay loam with only moderate

161 runoff and erosion potential. Leafu soils in the lowlands are very deep (>150 cm), poorly drained

162 silty clay to fine sandy loam that are typically along streams and valley bottoms where the high

163 water table is typically 90-150 cm deep.

164 ## Climate

165   Precipitation on Tutuila is caused by several mechanisms including cyclones and tropical

166 depressions, isolated thunderstorms, and orographic uplifting of trade-wind squalls over the high

167 (300-600 m), mountainous ridge that runs the length of the island. The ridge runs parallel to the

168 predominant wind direction, and does not cause a significant windward/leeward rainfall gradient

169 like many other Pacific Islands (Ferrier et al., 2013; Menking et al., 2013). Average annual

170 specific discharge (m^3/yr/km^2) shows little spatial variation across the island, irrespective of

171 watershed location or orientation (Dames & Moore, 1981). Precipitation increases with

172 elevation, from an average 2,380 mm/yr at the shoreline to 6,350 mm/yr at the highest elevation

173 on the island, averaging 3,800 mm/yr over the island from 1903 to 1973 (Eyre, 1989; Izuka et al.,

174 2005). In Faga'alu watershed, rainfall records show average annual precipitation is 6,350 mm at

175 Matafao Mtn. (653 m m.a.s.l) and 5,280 mm at Matafao Reservoir (249 m m.a.s.l.) and about 3,800

176 mm on the coastal plain (Craig, 2009; Dames & Moore, 1981; Perreault, 2010; Tonkin & Taylor

177 International Ltd., 1989; Wong, 1996). Mean annual potential evapotranspiration follows the

178 opposite trend, varying from 890 mm at high elevation to 1,150 mm at sea level (Izuka et al.,

179 2005). Tropical cyclones are erratic but occurred on average every 1-13 years from 1981-2014

180   (Craig, 2009) and bring intense rainfall, flooding, landslides, and high sediment yield

181   (Buchanan-Banks, 1979).

182   There are two subtle rainfall seasons: a drier winter season, from June through September

183   and a wetter summer season, from October through May (Izuka et al., 2005). During the drier

184   winter season, the island is influenced by relatively stronger, predominantly east to southeast

185   trade winds, lower temperatures, lower humidity and lower total rainfall. During the wetter

186   summer season the Inter-Tropical Convergence Zone (ITCZ) moves over the region, causing

187   light to moderate Northerly winds, higher temperatures, higher humidity, and higher total

188   rainfall. While total rainfall is lower in the drier tradewind season, large storm events are still

189   observed. Analysis of 212 peak discharges at 11 continuous-record gaging sites 1959-1990

190   showed 65% of annual peak flows occurred during the wet season and 35% of annual peak flows

191   occurred during the drier Tradewind season (Wong, 1996). Analysis of mean monthly rainfall

192   data for the period 1971-2000 showed that 75% of precipitation occurred in the wet season,

193   which includes 67% of the year (October-May), and 25% occurred in the dry season, which

194   covers 33% of the year (June-September) (Perreault, 2010; data from USGS rain gauges and

195   Parameter-elevation Relationships on Independent Slopes Model (PRISM) Climate Group (Daly

196   et al., 2008)).

197   Land Cover and Land Use

198   The predominant land cover in Faga'alu watershed is undisturbed vegetation (94.8%),

199   including forest (85.7%) and scrub/shrub (9.0%) on the steep hillsides (Table 1), based on a 1

200   m^2-resolution land cover map from NOAA's Ocean Service and Coastal Services Center (2010).

201   The upper watershed, draining to FG1 in Figure 1, is dominated by undisturbed rainforest on

202   steep hillslopes. The lower subwatershed, draining areas between FG1 and FG3 in Figure 1, has

203   steep vegetated hillslopes and a relatively small flat area in the valley bottom that is urbanized.

204   This settlement pattern is typical in the South Pacific and other volcanic islands, where their

205   small size and steep topography constrain development to valley bottoms near the coast (Bégin et

206   al., 2014). Compared to other watersheds on Tutuila, a relatively large portion of Faga'alu

207   watershed is urbanized (3.2% "High Intensity Developed" in Table 1), due to large areas of

208   impervious surface associated with the hospital and the numerous residences and businesses. A

209   small portion of the watershed (0.9%) is developed open space, which includes landscaped lawns

210   and parks. In addition to some small household gardens there are several small agricultural areas

211   of banana and taro on the steep hillsides. These agricultural plots were classified as grassland

212   (0.2% GA, Table 1) due to the high fractional grass cover in the plots. Farmers of these plots

213   receive technical assistance from the Natural Resource Conservation Service (NRCS) to mitigate

214   erosion. There are several small footpaths and unpaved driveways in the village, but most

215   unpaved roads are stabilized with compacted gravel and do not appear to be a major contributor

216   of sediment (Horsley-Witten, 2012). Longitudinal sampling of Faga'alu stream during low flow

217   conditions in 2011 showed significantly increased turbidity downstream of a bridge construction

218   site on the village road approximately 200 m downstream of FG2 (Curtis et al., 2011).

219   Construction of the bridge was completed in March 2012 and no longer increases turbidity.

220   An open-pit aggregate quarry covers 1.6 ha and accounts for the majority of the bare

221   land, which covers 1.1% of the Faga'alu watershed (Table 1). The quarry has been in continuous

222   operation since the 1960's by advancing into the steep hillside to quarry the underlying basalt

223   formation (Latinis et al., 1996). The overburden of soil and weathered rock was either piled up

224   on-site where it was eroded by storms, or was manually rinsed from crushed aggregate. With few

225   sediment runoff controls in place, sediment was discharged directly to Faga'alu stream. In 2011,

10

226 the quarry operators installed some sediment runoff management practices such as silt fences and

227 settling ponds (Horsley-Witten, 2011) but they were unmaintained and inadequate to control the

228 large amount of sediment mobilized during storm events (Horsley-Witten, 2012). During the

229 study period (2012-2014), additional sediment control measures were installed and some large

230 piles of overburden were naturally overgrown by vegetation (Figure 2), altering the sediment

231 availability. In late 2014, large sediment retention ponds were installed to mitigate sediment

232 runoff and work is underway to document the reduction in sediment loading (Messina and Biggs,

233 forthcoming; See Holst-Rice et al. (2015) for a full description of sediment mitigation efforts at

234 the quarry).

235   Three water impoundment structures were built in the early 20th century in the upper part

236 of the watershed for drinking water supply and hydropower but only the highest, Matafao

237 Reservoir, was ever connected to the municipal water system and has since fallen out of use

238 (Tonkin & Taylor International Ltd., 1989) (Figure 1). The dam at point FG1 has filled with

239 bedload sediment and flows over the spillway even at the lowest flows. We assume the other

240 reservoirs are similarly filled with coarse sediment and are not currently retaining fine suspended

241 sediment. A full description of stream impoundments is in Appendix 1.

242 Methods

243   The suspended sediment yield (SSY) in Faga'alu stream was measured at three sampling

244 points that drain key land covers we hypothesized would have different SSY: FG1 drains

245 undisturbed forest in the UPPER subwatershed (watershed boundary to FG1), FG2 drains

246 undisturbed forest and the quarry in the LOWER_QUARRY subwatershed (between FG1 and

247 FG2), and FG3 drains undisturbed forest and the village in the LOWER_VILLAGE

248   subwatershed (between FG2 and FG3) (Table 1). FG3 is also the watershed outlet for the

249   TOTAL watershed.

250   Calculating suspended sediment yield from individual storm events (SSY$_{EV}$)

251   SSY$_{EV}$ at FG1, FG2, and FG3 were calculated by integrating continuous estimates of

252   SSY, calculated from measured or modeled water discharge (Q) and measured or modeled

253   suspended sediment concentration (SSC) (Duvert et al., 2012):

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

where *SSY$_{EV}$* is suspended sediment yield (tons) for an event from t=0 at storm start to T=storm

end, *SSC* is suspended sediment concentration (mg/L), and *Q* is water discharge (L/sec), and *k*

converts from mg to tons (10^{-6}).

254   Storm events can be defined by precipitation (Hicks, 1990) or discharge parameters

255   (Duvert et al., 2012), and the method used to identify storm events on the hydrograph can

256   significantly influence the analysis of SSY$_{EV}$ (Gellis, 2013). Dunne and Leopold (1978) assert

257   that all hydrograph separation schemes are arbitrary and usually have little to do with the

258   processes that generate storm flow, but if a consistent method is used then at least the results of

259   different analyses can be compared. Graphical techniques may be implemented to separate the

260   hydrograph into baseflow and quickflow, using the start and end of quickflow as the start and

261   end of the storm event (Dunne and Leopold, 1978; Perreault, 2010). Storms can also be filtered

262   from the analysis by using various criteria such as minimum storm duration, time between

263   discharge peaks, minimum peak discharge, or more complex schemes using statistical

264   distributions of flow percentiles (Gellis, 2013; Lewis et al., 2001). More complex signal

265   processing methods can also be used, including finding the inflection point of the second

266 derivative of the hydrograph to determine the end of the storm event. However, complex events

267 occur where subsequent precipitation generates stormflow before the stream has returned to

268 baseflow. In these cases, the storm definition scheme can significantly affect the analysis of

269 storm sediment yields by separating or combining multiple hydrograph peaks. Due to the high

270 number of storm events and the prevalence of complex storm events recorded at the study site,

271 an automated approach that robustly separated complex events was desirable. The storm

272 definition approach used in this study performed baseflow separation with a digital filter signal

273 processing technique (Nathan and McMahon, 1990) embedded in the R-statistical package

274 EcoHydRology (Fuka et al., 2014). Only events with quickflow for at least one hour and peak

275 flow greater than 10% of baseflow were included in the analysis. This approach was easily

276 automated for application to a large number of events, and adequately separated complex storm

277 events with multiple hydrograph peaks (See Appendix 3 for example).

278 ## Data Collection Methods

279   Data on precipitation (P), water discharge (Q), suspended sediment concentration (SSC)

280 and turbidity (T) were collected during four field campaigns: January-March, 2012, February-

281 July 2013, January-March 2014, and October-December 2014, and several intervening periods of

282 unattended monitoring by instruments with data loggers. Field sampling campaigns were

283 scheduled to coincide with the period of most frequent storms in the November-May wet season,

284 though large storms were sampled throughout the year.

285 *Precipitation*

286   Precipitation (P) was measured at three locations in Faga'alu watershed using Rainwise

287 RAINEW tipping-bucket rain gages (RG1 and RG2) and a Vantage Pro Weather Station (Wx)

288 (Figure 1). Data at RG2 was only recorded January-March, 2012, to determine a relationship

289   between elevation and precipitation in the LOWER subwatershed. While previous data suggest

290   that precipitation increases with elevation (Izuka et al., 2005), here we do not calculate

291   watershed-mean precipitation, and instead use precipitation depth at RG1 to indicate the depth of

292   rainfall during a storm event. Most sheetwash and rill erosion, which depends on rainfall

293   intensity and erosivity, occurred at the quarry, near the location of RG1. Rainfall data from RG1

294   is therefore most representative of rainfall at the quarry. The total event precipitation (Psum) and

295   event Erosivity Index (EI30) were calculated using data from RG1, with data gaps filled by 15

296   min interval precipitation data from Wx.

297   *Water Discharge*

298   Stream gaging sites were chosen to take advantage of an existing control structure (FG1)

299   and a stabilized stream cross section (FG3) (Duvert et al, 2010). At FG1 and FG3, Q was

300   calculated from stream stage measurements taken at 15 minute intervals and a stage-Q rating

301   curve calibrated to manual Q measurements. Q was measured in the field under both baseflow

302   and stormflow conditions by the area-velocity method (AV) using a Marsh-McBirney flowmeter

303   to measure flow velocity and channel surveys of cross-sectional area (Harrelson et al., 1994;

304   Turnipseed and Sauer, 2010). The highest recorded stage was higher than the highest stage with

305   measured Q, so the stage-Q rating at FG3 was extrapolated using Manning's equation, calibrating

306   Manning's n (0.067) to the Q measurements. At FG1, the flow control structure is a masonry

307   ogee spillway crest of a defunct stream capture. Since the highest recorded stage (120 cm) was

308   higher than the highest stage with measured Q (17 cm), and the flow structure did not meet the

309   assumptions for using Manning's equation to predict flow, the HEC-RAS model was used to

310   create the stage-Q relationship (Brunner, 2010). See Appendix 2 for details of the cross sections

311   and rating curves.

14

312   A suitable site for stream gaging was not present at the outlet of the LOWER_QUARRY

313   subwatershed (FG2), so water discharge at FG2 was calculated as the product of the specific

314   water discharge from FG1 (m³/0.9 km²) and the watershed area draining to FG2 (1.17 km²). This

315   assumes that specific water discharge from the subwatershed above FG2 is similar to above FG1.

316   Discharge may be higher from the quarry surface, which represents 5.7% of the

317   LOWER_QUARRY subwatershed, so Q, and thus SSY from the quarry are a conservative,

318   lower bound estimate, particularly during small events when specific discharge from the UPPER

319   watershed was small relative to specific discharge from the quarry. The quarry surface is

320   continually being disturbed, sometimes with large pits excavated and refilled in the course of

321   weeks, as well as intentional water control structures implemented over time. Given the changes

322   in the contributing area of the quarry, estimates of water yield from the quarry were uncertain, so

323   we assumed a uniform specific discharge for the whole LOWER_QUARRY subwatershed.

324   *Continuous Suspended Sediment Concentration*

325   Continuous SSC at 15 minute intervals was estimated from 1) linear interpolation of SSC

326   measured from water samples, and 2) 15 min interval turbidity data (T) and a T-SSC relationship

327   calibrated to stream water samples collected over a range of Q and SSC.

328   Stream water samples were collected by grab sampling with 500 mL HDPE bottles at

329   FG1, FG2, and FG3. At FG2, water samples were also collected at 30 min intervals during storm

330   events by an ISCO 3700 Autosampler triggered by a stage height sensor. Samples were analyzed

331   for SSC on-island using gravimetric methods (Gray, 2014; Gray et al., 2000). Water samples

332   were vacuum filtered on pre-weighed 47mm diameter, 0.7 um Millipore AP40 glass fiber filters,

333   oven dried at 100 C for one hour, cooled and weighed to determine SSC (mg/L).

334   Interpolation of SSC values from grab samples could only be performed if at least three

335   stream water samples were collected during a storm event (Nearing et al., 2007), and if an SSC

336   sample was collected within 30 minutes of peak Q. SSC was assumed to be zero at the beginning

337   and end of each storm if no grab sample data was available for those times (Lewis et al., 2001).

338   Turbidity (T) was measured at FG1 and FG3 using three types of turbidimeters: 1)

339   Greenspan TS3000 (TS), 2) YSI 600OMS with 6136 turbidity probe (YSI), and 3) Campbell

340   Scientific OBS500 (OBS). All turbidimeters were permanently installed in protective PVC

341   housings near the streambed where the turbidity probe would be submerged at all flow

342   conditions, with the turbidity probe oriented downstream. Despite regular maintenance, debris

343   fouling during storm and baseflows was common and caused data loss during several storm

344   events (Lewis et al., 2001).

345   The T-SSC relationship can be unique to each region, stream, instrument or even each

346   storm event (Lewis et al., 2001), and can be influenced by water color, dissolved solids and

347   organic matter, temperature, and the shape, size, and composition of sediment. However, T has

348   proved to be a robust surrogate measure of SSC in streams (Gippel, 1995), and is most accurate

349   when a unique T-SSC relationship is developed for each instrument separately, using in situ grab

350   samples under storm conditions (Lewis, 1996). A unique T-SSC relationship was developed for

351   each turbidimeter, at each location, using T data and SSC samples from storm periods only (r^2

352   values 0.79-0.99). See Appendix 4 for details on the T-SSC relationships.

353   *Cumulative Probable Error (PE)*

354   Uncertainty in SSY_{EV} estimates arises from both measurement and model errors,

355   including stage-Q and T-SSC (Harmel et al., 2006). The Root Mean Square Error (RMSE)

356   method estimates the "most probable value" of the cumulative or combined error by propagating

16

357   the error from each measurement and modeling procedure to the final SSY$_{EV}$ calculation

358   (Topping, 1972). The resulting cumulative probable error (PE) is the square root of the sum of

359   the squares of the maximum values of the separate errors:

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

where *PE* is the cumulative probable error for individual measured values (±%), E_{Qmeas} is

uncertainty in Q measurements (±%), $E_{SSCmeas}$ is uncertainty in SSC measurements (± %),

E_{Qmod} is uncertainty in Q modeled by the Stage-Q relationship (RMSE, as ±% of the mean

observed Q), E_{SSCmod} is uncertainty in SSC modeled by the T-SSC relationship (RMSE, as ± %

of the mean observed SSC) (Harmel et al., 2009).

360   E_{Qmeas} and $E_{SSCmeas}$ were estimated using lookup tables from the DUET-H/WQ software

361   tool (Harmel et al., 2009). The effect of uncertain SSY$_{EV}$ estimates may complicate conclusions

362   about contributions from subwatersheds, anthropogenic impacts, and SSY$_{EV}$-Storm Metric

363   relationships. This is common in sediment yield studies where successful models estimate SSY

364   with ±50-100% accuracy (Duvert et al., 2012) but the difference in SSY from undisturbed and

365   disturbed areas was expected to be much larger than the cumulative uncertainty. PE was

366   calculated for SSY$_{EV}$ from the UPPER and TOTAL watersheds, but not calculated for SSY$_{EV}$

367   from the LOWER subwatershed since it was calculated as the difference of SSY$_{EV\_UPPER}$ and

368   SSY$_{EV\_TOTAL}$.

369   Relationship of sediment load to sediment budget

370   We use the measured sediment yield at three locations to quantify the in-stream

371   suspended sediment budget. Other components of sediment budgets include channel erosion and

372   or channel and floodplain deposition (Walling and Collins, 2008). Sediment storage and

17

373   remobilization can significantly complicate the interpretation of in-stream loads, and complicate

374   the identification of a land use signal. In Faga'alu, the channel bed is predominantly large

375   volcanic cobbles and coarse gravel, with no significant deposits of fine sediment. Upstream of

376   the village, the valley is very narrow with no floodplain. In the downstream reaches of the lower

377   watershed, where fines might deposit in the floodplain, the channel has been stabilized with

378   cobble reinforced by fencing, so overbank flows and sediment deposition on the floodplain are

379   not observed. We therefore assume that channel erosion and channel and floodplain deposition

380   are insignificant components of the sediment budget, so the measured sediment yields at the

381   three locations reflect differences in hillslope sediment supply. Minimal sediment storage also

382   reduces the lag time between landscape disturbance and observation of sediment at the watershed

383   outlet.

384   Quantifying SSY from disturbed and undisturbed subwatersheds

385   A main objective for this study was to quantify anthropogenic changes in SSY_{EV_TOTAL}

386   as measured at FG3. Relative contributions to SSY_{EV_TOTAL} from undisturbed and human-

387   disturbed areas were assessed using two approaches: 1) comparing SSY_{EV} contributions from

388   subwatersheds for each storm and the average of all storms, and 2) the Disturbance Ratio (DR).

389   The percent contributions of subwatersheds to SSY_{EV_TOTAL} were calculated from SSY_{EV}

390   measured at FG1, FG2, and FG3 (Figure 1). SSY_{EV} from the UPPER subwatershed was

391   measured at FG1 ($SSY_{EV\_UPPER} = SSY_{EV\_FG1}$). SSY_{EV} from the LOWER subwatershed was

392   calculated as $SSY_{EV\_LOWER} = SSY_{EV\_FG3} - SSY_{EV\_FG1}$. Where SSY_{EV} data at FG2 were also

393   available, the contributions from the quarry subwatershed ($SSY_{EV\_LOWER\_QUARRY} = SSY_{EV\_FG2} -$

394   SSY_{EV_FG1}), and village subwatershed ($SSY_{EV\_LOWER\_VILLAGE} = SSY_{EV\_FG3} - SSY_{EV\_FG2}$) were

395   calculated separately.

396   Land cover in the LOWER subwatershed includes both undisturbed and human-disturbed

397   surfaces. To calculate SSY_{EV} from disturbed areas, SSY_{EV} from undisturbed areas was estimated

398   using the specific SSY_{EV} ($sSSY_{EV}$ tons/km²) from the UPPER subwatershed multiplied by the

399   undisturbed area in the LOWER subwatershed:

$$SSY_{EV\_distrb} = SSY_{EV\_subws} - \left(sSSY_{EV\_UPPER} * Area_{undist}\right)$$ Equation 3

where SSY_{EV_distrb} is SSY_{EV} from disturbed areas only (tons), SSY_{EV_subws} is SSY_{EV} (tons)

measured from the disturbed subwatershed (e.g. SSY_{EV_FG3}- SSY_{EV_FG2}), $sSSY_{EV\_UPPER}$ is

specific SSY_{EV} (tons/km2) from the UPPER subwatershed (SSY_{EV_FG1}), and $Area_{undist}$ is the

area of undisturbed forest in the disturbed subwatershed (km^2).

400   The disturbance ratio (DR) is the ratio of SSY_{EV} from the watershed under current

401   conditions to SSY_{EV} under pre-disturbance conditions, estimated using $sSSY_{UPPER}$:

$$DR = \frac{SSY_{EV\_subw}}{A_{subw} * sSSY_{EV\_UPPER}}$$ Equation 4

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

402   Both Equation 3 and 4 assume that the whole watershed was originally covered in forest,

403   and $sSSY_{EV}$ from forested areas in the LOWER subwatershed equals $sSSY_{EV}$ from the

404   undisturbed UPPER watershed. SSY_{EV} from the disturbed portions of the LOWER subwatershed

405   (Equation 3) was used to calculate a DR for just the disturbed areas in the LOWER

406   subwatershed.

407   Predicting event suspended sediment yield (SSY_{EV})

408   Four storm metrics were tested as predictors of SSY_{EV}: total event precipitation (Psum),

409   event Erosivity Index (EI30) (Hicks, 1990; Kinnell, 2013), total event water discharge (Qsum),

410   and maximum event water discharge (Qmax) (Duvert et al., 2012; Rodrigues et al., 2013).

411   SSY_{EV} and the discharge metrics (Qsum and Qmax) were normalized by watershed area to

412   compare different sized watersheds.

413   The relationship between SSY_{EV} and storm metrics is often best fit by a power law

414   function:

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

where X is a storm metric, and the regression coefficients α and β are obtained by ordinary

least squares regression on the logarithms of SSY_{EV} and X (Basher et al., 2011; Duvert et al.,

2012; Hicks, 1990). Model fits for each storm metric were compared using coefficients of

determination (r^2) and Root Mean Square Error (RMSE). The correlation between storm

metrics (X) and SSY_{EV} was also quantified using both parametric (Pearson) and non-

parametric (Spearman) correlation coefficients.

415   The regression coefficients (α and β) for the UPPER and TOTAL watersheds were tested

416   for statistically significant differences using Analysis of Covariance (ANCOVA) (Lewis et al.,

417   2001). A higher intercept (α) for the human-disturbed watershed indicates higher sediment yield

418   for the same size storm event, compared to sediment yield from undisturbed areas. A difference

419   in slope (β) would indicate the relative sediment contributions from the subwatersheds change

420   with increasing storm size. If regression slopes for the UPPER and TOTAL watersheds are

421   significantly different, it supports the conclusion that the effect of human-disturbance changes

422   with storm size.

423   Annual estimates of SSY and sSSY

424   Annual estimates of SSY and sSSY were calculated to compare Faga'alu with other

425   watersheds reported in the literature. A continuous annual time-series of SSY was not possible at

426 the study site due to the discontinuous field campaigns and failure of or damage to the

427 turbidimeters during some months. Continuous records of P and Q were available for 2014, so

428 the Psum-SSY_{EV} and Qmax-SSY_{EV} models (Equation 5) were used to predict SSY_{EV} for all

429 storms in 2014 (Basher et al., 1997). Construction of sediment mitigation structures at the quarry

430 began in October 2014, greatly reducing SSY_{EV} from the LOWER_QUARRY subwatershed

431 (unpublished data), so the Qmax-SSY_{EV} relationship developed prior to the mitigation was used

432 to calculate the annual pre-mitigation sediment yield. For storms with no Qmax data at FG3,

433 Qmax was predicted from a linear regression between Qmax at FG1 and Qmax at FG3 for the

434 study period ($R^2 = 0.88$).

435   Annual SSY and sSSY were also estimated by multiplying SSY_{EV} from measured storms

436 by the ratio of annual storm precipitation (P_{sann}) to the precipitation measured during storms

437 where SSY_{EV} was measured (P_{smeas}):

$$SSY_{ann} = SSY_{EV\_meas} * \frac{P_{EV\_ann}}{P_{EV\_meas}}$$
Equation 6

where SSY_{ann} is estimated annual SSY from storms, SSY_{EV_meas} is SSY_{EV} from sampled storms

(all, Tables 2 and 4), P_{EV_meas} is precipitation measured during the sampled storms, and P_{EV_ann}

is the precipitation during all storm events defined by the hydrograph separation.

438   Equation 6 assumes that the sediment yield per mm of storm precipitation is constant

439 over the year, and that the size distribution of storms has no effect on SSY_{EV}, though there is

440 some evidence that SSY_{EV} increases exponentially with storm size (Lewis et al., 2001; Rankl,

441 2004). Equation 6 also ignores sediment yield during non-storm periods, which is justified by the

442 low SSC and Q observed between storms.

Results

Field Data Collection

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.

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-

464   September dry season. The largest event in the three year monitoring period was observed in the

465   dry season (August 2014).

Storm Events

467   A total of 210 storm events were identified using hydrograph separation on the Q data at

468   FG1 and FG3 between January, 2012, and December 2014. 169 events had simultaneous Q data

469   at FG1 and FG3 (Appendix 3, Table 1). SSC data from T or interpolated grab samples were

470   recorded during 112 events at FG1, and 74 events at FG3. Of those storms, 42 events had data

471   for P, Q, and SSC at both FG1 and FG3 to calculate SSY_{EV} from the LOWER subwatershed.

472   SSY data from interpolated grab samples were collected at FG2 for 8 storms to calculate SSY_{EV}

473   from the LOWER_QUARRY and LOWER_VILLAGE subwatersheds separately. Storm event

474   durations ranged from 1 hour to 2 days, with mean duration of 13 hours.

475   Most storm events showed a typical pattern, where a short period of intense rainfall

476   caused a rapid increase in SSC downstream of the quarry (FG2) while SSC remained low at the

477   undisturbed forest site (FG1) (Figure 4). The highest SSC was typically observed at FG2, with

478   slightly lower and later peak SSC observed at FG3. SSC downstream of the undisturbed forest

479   (FG1) typically increased more slowly, remained lower, and peaked later than the disturbed sites

480   downstream of the quarry (FG2) and the village (FG3). Though peak SSC was highest at FG2,

481   the highest SSY was measured at FG3 due to the addition of storm runoff and sediment from the

482   larger subwatershed draining to FG3.

Suspended Sediment Concentration

484   From January 6, 2012, to October 1, 2014, 506 water samples were collected at FG1

485   (n=59), FG2 (n=90 grab samples, n=198 from the Autosampler), and FG3 (n=159). Mean (μ)

486   and maximum SSC of water samples, collected during non-stormflow and stormflow periods by

487   grab and autosampler, were lowest at FG1 (μ=28 mg/L, max=500 mg/L), highest at FG2 (μ=337

488   mg/L, max=12,600 mg/L), and in between at FG3 (μ=148 mg/L, max=3,500 mg/L). At FG1,

489   24% of grab samples (n=14) were collected during non-stormflow, μ=8 mg/L (Figure 5a); 76%

490   of grab samples (n=45) were collected during stormflow, μ= 35 mg/L (Figure 8b). At FG2, 23%

491   of grab samples (n=21) were collected during non-stormflow, μ= 105 mg/L; 77% of grab

492   samples (n=69) were collected during stormflow, μ= 409 mg/L. At FG3, 25% of samples (n=39)

493   were collected during non-stormflow, μ= 52 mg/L; 75% of samples (n=120) were collected

494   during stormflow, μ= 179 mg/L. This pattern of SSC values suggests that little sediment is

495   contributed from the forest upstream of FG1, followed by a large input of sediment between FG1

496   and FG2, and then SSC is diluted by addition of stormflow with lower SSC between FG2 and

497   FG3.

498   Probability plots of the SSC data collected at FG1, FG2 and FG3 showed they were

499   highly non-normal, so non-parametric tests for statistical significance were applied. The results

500   of the Kruskall-Wallis test were significant for non-stormflow ($p<10^{-4}$) and stormflow ($p<10^{-4}$);

501   means of SSC samples were significantly different among all three locations. The results of the

502   pair-wise Mann-Whitney test between FG1 and FG2 were significant (non-stormflow, $p<10^{-4}$;

503   stormflow, $p<10^{-4}$), but between FG2 and FG3 were significant for non-stormflow ($p<0.05$) but

504   not for stormflow ($p>0.10$); means of SSC samples at FG1 and FG2 were significantly different,

505   but FG2 and FG3 were not.

506   SSC varied by several orders of magnitude for a given Q at FG1, FG2, and FG3 due to

507   significant hysteresis observed during storm periods (Figure 6). At FG1, variability of SSC

508   during stormflow was assumed to be caused by randomly occurring landslides or mobilization of

509   sediment stored in the watershed during large storm events. The maximum SSC sampled

510   downstream of the undisturbed forest, at FG1 (500 mg/L), was sampled on 04/23/2013 at high

511   discharge (QFG1= 3,724 L/sec) (Figure 6a). Anecdotal and field observations reported higher

512   than normal SSC upstream of the quarry during the 2013 field season, possibly due to landsliding

513   from previous large storms (G. Poysky, pers. comm.).

514   At FG2 and FG3, additional variability in the Q-SSC relationship was due to the

515   changing sediment availability associated with quarrying operations and construction in the

516   village. The high SSC values observed downstream of the quarry (FG2) during low Q were

517   caused by two mechanisms: 1) precipitation events that did not result in stormflow, but generated

518   runoff from the quarry with high SSC and 2) washing fine sediment into the stream during rock

519   crushing operations at the quarry.

520   The maximum SSC sampled at FG2 (12,600 mg/L) and FG3 (3,500 mg/L) were sampled

521   during the same rainfall event (03/05/2012), but during low Q (Q_FG3=287 L/sec) (Figure 6b-c).

522   During this event, brief but intense precipitation caused high sediment runoff from the quarry.

523   SSC was diluted further downstream of the quarry at FG3 by the addition of runoff with lower

524   SSC from the village.

525   Given the close proximity of the quarry to the stream, SSC downstream of the quarry can

526   be highly influenced by mining activity like rock extraction, crushing, and/or hauling operations.

527   During 2012, a common practice for removing fine sediment from crushed aggregate was to

528   rinse it with water pumped from the stream. In the absence of retention structures the fine

529   sediment was then discharged directly into the stream, causing high SSC during baseflow periods

530   with no precipitation in the preceding 24 hours (solid symbols, Figure 6b-c). Riverine discharge

531   of fine sediment rinsed from aggregate was discontinued in 2013. In 2013 and 2014, waste

25

532   sediment was piled on-site and severe erosion of these changing stockpiles caused high SSC

533   during storm events.

534   *Cumulative Probable Error (PE)*

535   Cumulative Probable Error (RMSE %) for SSY_{EV} estimates at FG1 and FG3 were

536   calculated from the measurement errors for Q (8.5%) and SSC grab samples (16.3%), and the

537   model errors of the respective stage-Q and T-SSC relationships for that location. Cumulative

538   Probable Errors (PE) in SSY_{EV} were 28-49% (μ=43%) at FG1 and 36-118% (μ=94%) at FG3.

539   The measurement error (RMSE) for Q at FG1 and FG3 was 8.5 %, which included error

540   in the area-velocity measurements (6%), continuous Q measurement in a natural channel (6%),

541   pressure transducer error (0.1%), and streambed condition (firm, stable bed=0%) (DUET-H/WQ

542   look-up table (Harmel et al., 2006)). The model errors (RMSE) were 32% for the stage-Q rating

543   curve using Manning's equation at FG3, and 22% using HEC-RAS at FG1.

544   The measurement error (RMSE) for SSC was 16.3%, which included errors for sample

545   collection and analysis. Sample collection error consisted of interpolating over a 30 min interval

546   (5%) and sampling during stormflows (3%). Sample analysis error was from measuring SSC by

547   filtration (3.9%). The model errors (RMSE) of the T-SSC relationships were 16% (4 mg/L) for

548   the YSI and TS turbidimeters at FG1, 113% (348 mg/L) for the YSI turbidimeter at FG3, and

549   46% (48 mg/L) for the OBS turbidimeter at FG3.

550   Comparing SSY_{EV} from disturbed and undisturbed subwatersheds

551   SSY_{EV} was measured simultaneously at FG1 and FG3 for 42 storms (Table 2).

552   SSY_{EV_TOTAL} was 129.2±121.4 tons (72.6±68.2 tons/km²), with 17.0±7.3 tons (18.8±8.1

553   tons/km²) from the UPPER subwatershed and 112.2 tons (127.5 tons/km²) from the LOWER

554   subwatershed. The UPPER and LOWER subwatersheds are similar in size (0.90 km² and 0.88

555   km²) but SSY_{EV_UPPER} accounted for an average of just 13% and SSY_{EV_LOWER} for 87% of SSY_{EV}

556   at the watershed outlet (Table 2). The DR estimated from $sSSY_{EV\_UPPER}$ (=18.8 tons/km²) and

557    $sSSY_{EV\_LOWER}$ (Equation 4) suggests $sSSY_{EV}$ has increased by 6.8x in the LOWER

558   subwatershed, and 3.9x for the TOTAL watershed.

559   SSY_{EV} from the undisturbed forest areas in the LOWER watershed was estimated to be

560   14.9 tons for the 42 events in Table 2 (Equation 3), so SSY_{EV} from the disturbed areas was 97.3

561   tons (Table 3). Approximately 87% of SSY_{EV_LOWER} was from disturbed areas, despite the

562   disturbed areas only accounting for 10.1% of the LOWER subwatershed area (0.089 km²).

563   Similarly, despite only 5.2% of the TOTAL watershed being disturbed, SSY from disturbed

564   areas accounted for 75% of SSY_{EV_TOTAL}. sSSY from disturbed areas in the LOWER

565   subwatershed was 1,095 tons/km², or 58x the sSSY of undisturbed forest.

566   It was hypothesized the quarry was a key sediment source, but SSY_{EV} was measured

567   simultaneously at FG1, FG2, and FG3 for only 8 of the storms in Table 2. SSY_{EV} was calculated

568   separately from the LOWER subwatershed containing the quarry ($SSY_{EV\_LOWER\_QUARRY}$) and

569   LOWER subwatershed containing the village below the quarry ($SSY_{EV\_LOWER\_VILLAGE}$) for those

570   8 storms (Table 4). For the 8 storms in Table 4, SSY_{EV_TOTAL} was 46 tons with an average of

571   29% from the UPPER subwatershed, 36% from the LOWER_QUARRY subwatershed, and 35%

572   from the LOWER_VILLAGE subwatershed. sSSY from the UPPER, LOWER_QUARRY, and

573   LOWER_VILLAGE subwatersheds, and the TOTAL watershed was 15, 61, 27, and 26 tons/km²,

574   respectively. The results from the smaller sample of storms in Table 4, show a slightly lower

575   increase in SSY from the TOTAL watershed, 1.7x, but show the sSSY has increased by 4.08x in

576   the LOWER_QUARRY subwatershed and 1.8x in the LOWER_VILLAGE subwatershed.

577   Very small fractions of the subwatershed areas are disturbed, yet roughly 77% of SSY

578     $_{\text{EV\_LOWER\_QUARRY}}$ (6.5% disturbed) and 51% of SSY $_{\text{EV\_LOWER\_VILLAGE}}$ (11.7% disturbed)

579   subwatersheds was from disturbed areas. Similarly, despite only 5.2% of the TOTAL watershed

580   being disturbed, 75-45% of SSY $_{\text{EV\_TOTAL}}$ was from disturbed areas (Tables 3 and 5). Bare land

581   in the LOWER_QUARRY subwatershed significantly increased sSSY$_{\text{LOWER\_QUARRY}}$ and

582   sSSY$_{\text{TOTAL}}$, and contributed the majority of SSY from disturbed areas in Faga'alu watershed.

583   sSSY from disturbed areas in the UPPER (37.0 tons/km²), LOWER_QUARRY (721.6 tons/km²),

584   and LOWER_VILLAGE subwatersheds (116.2 tons/km²) suggested that disturbed areas increase

585   sSSY over forested conditions by 49x and 8x in the LOWER_QUARRY and

586   LOWER_VILLAGE subwatersheds, respectively. Human disturbance in the

587   LOWER_VILLAGE subwatershed also increased SSY above natural levels but the magnitude of

588   disturbance was much lower than the quarry.

589   Predicting SSY$_{\text{EV}}$ from storm metrics

590   SSY$_{\text{EV}}$ from the UPPER and TOTAL watersheds was correlated with each of the four

591   storm metrics tested (Figure 7), though the correlations with precipitation metrics were poor in

592   the heavily forested UPPER watershed (Table 6). Pearson and Spearman correlation coefficients

593   were similar, meaning the relationships were mostly linear in log-log space. Significant scatter

594   was observed around all models, which reflects the changing sediment availability at the quarry

595   and village, and the natural variability in the watershed response for different storm events.

596   Qsum was the best predictor of SSY$_{\text{EV}}$ for the UPPER watershed, and Psum was the best

597   predictor for the TOTAL watershed, though Qmax was nearly as good a predictor for both

598   watersheds. SSY$_{\text{EV}}$ is calculated from Q so it is expected that Qsum should correlate closely with

599   SSY$_{\text{EV}}$, as observed in other studies (Duvert et al., 2012; Rankl, 2004). Indeed the Qsum model

28

600 for the UPPER watershed showed the highest coefficient of determination (r^2), lowest RMSE,

601 and highest Pearson and Spearman correlation coefficients (Table 6). Psum showed an equally

602 high r^2 and a lower RMSE, but only for the TOTAL subwatershed. This suggests that sediment

603 production is more related to discharge processes in the UPPER subwatershed, and more related

604 to precipitation processes in the LOWER subwatershed. Discharge metrics were also highly

605 correlated with SSY_{EV} in the TOTAL watershed, suggesting discharge metrics are good

606 predictors in both disturbed and undisturbed watersheds. Qmax was not the best predictor in

607 either watershed, but performed well in both watersheds, with similar correlation statistics to

608 both Qsum and Psum models. Most of the scatter in the Qmax-SSY_{EV} relationship is observed

609 for small events, and Qmax correlated strongly with the largest SSY_{EV} values when most of the

610 annual sediment load is generated.

611 Precipitation was measured at the quarry, which may reflect precipitation characteristics

612 more accurately in the LOWER than the UPPER watershed. SSY from the LOWER

613 subwatershed is hypothesized to be mostly generated by hillslope erosion by sheetwash and rill

614 formation at the quarry and on dirt roads, and agricultural plots, whereas SSY from the UPPER

615 subwatershed is hypothesized to be mainly from channel processes and mass wasting. Mass

616 wasting can contribute large pulses of sediment which can be deposited near or in the streams

617 and entrained at high discharges during later storm events. Given the high correlation

618 coefficients between SSY_{EV} and Qmax in both watersheds, Qmax may be a promising predictor

619 that integrates both precipitation and discharge processes.

620 In all models, SSY_{EV} from the TOTAL watershed was higher than from the UPPER

621 watershed for the full range of measured storms with the exception of a few events that are

622 considered outliers. These events could be attributed to measurement error or to landslides in the

29

623   UPPER subwatershed and the increased sediment supply for that specific event. The separation

624   of multi-peak storm events, storm sequence, and antecedent conditions may also play a role.

625   While the climate on Tutuila is tropical, without strong seasonality, periods of low rainfall can

626   persist for several weeks, perhaps altering the water and sediment dynamics in the subsequent

627   storm events.

628   All model intercepts (α) were significantly different ($p<0.01$), but only the Qsum-SSY$_{EV}$

629   model showed significantly different ($p<0.01$) slopes (β). The Qsum-SSY$_{EV}$ models indicate that

630   SSY$_{EV}$ from the UPPER and TOTAL watersheds converge at higher Qsum values. Conversely,

631   the Psum- and Qmax-SSY$_{EV}$ models show no change in relative contributions of SSY over the

632   range of storm sizes (Figure 7).

633   The relative contribution from the human-disturbed watershed was hypothesized to

634   diminish with increasing storm size. The results from precipitation metrics and discharge metrics

635   were contradictory. The relative contribution of SSY$_{EV}$ from the human-disturbed watershed

636   decreases with storm size in the Qsum-SSY$_{EV}$ model, but the Psum- and Qmax-SSY$_{EV}$ models

637   show no change in relative contributions over increasing storm size (Figure 7). It was

638   hypothesized that SSY$_{EV}$ from natural areas would become the dominant source for larger storm

639   events, but the DR remains high for large storm events due to the naturally low SSY$_{EV}$ from

640   natural forest areas in Faga'alu watershed. This suggests that disturbed areas were not supply

641   limited for the range of sampled storms.

642   Annual estimates of SSY and sSSY

643   Estimates of annual sSSY depended on which predictor was used to estimate SSY$_{EV}$.

644   Annual sSSY from the UPPER and TOTAL watersheds was 14 tons/km²/yr and 75 tons/km²/yr,

645   respectively, as predicted by Psum-SSY$_{EV}$ relationship, and 68 tons/km²/yr and 247 tons/km²/yr,

646 respectively using the Qmax-SSY$_{EV}$ relationship (Table 7). The large difference in sSSY

647 between the two methods was due to higher scatter about the Psum-SSY$_{EV}$ relationship for large

648 events compared with the Qmax-SSY$_{EV}$. These results suggest the UPPER watershed contributed

649 14%, and the LOWER subwatershed contributed 86% of annual SSY from the TOTAL

650 watershed.

651 In order to compare with SSY estimated from the Psum-SSY$_{EV}$ and Qmax-SSY$_{EV}$

652 relationships, annual SSY was also calculated using Equation 6 for three sets of storm events: a)

653 all events with SSY$_{EV}$ data, including those where SSY$_{EV}$ data were only available for a single

654 site; b) only events where data was available for both UPPER (FG1) and TOTAL (FG3) and c)

655 only events where data was available for UPPER (FG1), LOWER_QUARRY (FG2), and

656 TOTAL (FG3). Including all storms (method a) will provide the best estimate at a given location,

657 while b) and c) allow more direct comparison of different subwatersheds. Continuous records of

658 Q and precipitation in 2014 showed annual storm precipitation (P$_{sann}$) was 2,770 mm,

659 representing 69% of total annual precipitation (3,709 mm). All storms with measured SSY$_{EV}$ at

660 FG1 from 2012-2014 included 3,457 mm of precipitation (P$_{smeas}$), or 125% of P$_{sann}$, so estimated

661 annual SSY from the UPPER subwatershed from Equation 6 was 41 tons/yr (45 tons/km²/yr). All

662 storms with measured SSY$_{EV}$ at FG3 from 2012-2014 included 2,628 mm of precipitation, or

663 95% of expected annual storm precipitation so estimated annual SSY from the TOTAL

664 watershed was 428 tons/yr (241 tons/km²/yr). These results suggest the UPPER watershed

665 contributed 10%, and the LOWER subwatershed contributed 90% of annual SSY from the

666 TOTAL watershed.

667 For storms with measured SSY$_{EV}$ at both FG1 and FG3 (Table 2), P$_{EVmeas}$ was 1,004 mm,

668 or 36% of P$_{EVann}$. From Equation 6, annual SSY increased from the UPPER (46 tons/yr),

31

669   LOWER (310 tons/yr), and TOTAL watershed (360 tons/yr). Annual sSSY increased from the

670   UPPER (51 tons/km²/yr), LOWER (350 tons/km²/yr), and TOTAL watershed (200 tons/km²/yr),

671   and, respectively.

672   For storms with measured SSY_{EV} at FG1, FG2, and FG3 (Table 4), P_{EVmeas} was 299 mm,

673   or 11% of P_{EVann}. Annual SSY increased from the UPPER (120 tons/yr), LOWER_QUARRY

674   subwatershed (150 tons/yr), LOWER_VILLAGE subwatershed (150 tons/yr), LOWER

675   subwatershed (300 tons/yr), and TOTAL watershed (420 tons/yr). Annual sSSY increased from

676   the UPPER (140 tons/km²/yr), LOWER_QUARRY (560 tons/km²/yr), LOWER_VILLAGE (250

677   tons/km²/yr), LOWER (340 tons/km²/yr), and TOTAL watershed 240 tons/km²/yr.

678   Overall, the Qmax model and Equation 6 using all events gave similar estimates of

679   annual SSY at both the UPPER watershed (41-61 tons/yr) and the total watershed (428-439

680   tons/yr). The accuracy of the Psum model was compromised by significant scatter for large

681   events, while the Qsum model had significantly less scatter for large events. The eight storms

682   sampled at all three locations (Table 4) had unusually high loads from the upper watershed but

683   similar SSY from the lower watershed, likely resulting in a low estimate of sediment loading and

684   DR from the quarry.

685   Discussion

686   Methods for quantifying human impact

687   Event-wise measurement of SSY_{EV} allowed rapid quantification of sediment loading

688   from natural and human-disturbed areas. Event wise analysis was useful because hysteresis and

689   interstorm variability caused significant scatter in the instantaneous Q-SSC relationship. While

690   the instantaneous Q-SSC relationship illustrated large increases in SSC downstream of the

32

691 quarry, the hysteresis and interstorm variability meant that a single Q-SSC relationship could not

692 be used to estimate of sediment loading, which complicated detection of human impact on

693 sediment concentrations and yield. Measurement of SSY_{EV} allows comparison of similar size

694 storms to determine change over space and time without problems of interannual variability in

695 precipitation totals, and the simple regression models that predict annual sediment load from

696 either precipitation or stormflow measurements eliminate the need for long-term field work to

697 estimate annual total yields. From a management perspective, the event-wise approach to

698 estimating human impacts on sediment is less expensive than efforts to measure annual yields

699 since it does not require a full year of monitoring and can be rapidly conducted if mitigation or

700 disturbance activities are already planned. With predictive models of SSY_{EV} that are based on an

701 easily-monitored storm metric like maximum event discharge, SSY_{EV} can be modeled in the

702 future to compare with either post-mitigation or post-disturbance SSY_{EV}.

703 The estimation of human impact on sediment loads was facilitated by the spatial

704 arrangement of disturbances and by the lack of significant sediment storage in the watershed. In

705 Faga'alu watershed, and other similar steep watersheds, human-disturbance is often constrained

706 to the lower watershed, and sediment yields from these key sources can be measured separately

707 from the undisturbed forest upstream. Reid and Dunne (1996) argue that in cases where there is a

708 clear management question and the study area can be divided into sub-units, a sediment budget

709 can be rapidly developed with only a few field measurements and limited periods of field

710 monitoring. The use of event-wise sampling in subwatersheds with specific land uses allowed for

711 separation of different sources to the sediment budget.

Interpreting slope and intercept of the Qmax-SSY$_{EV}$ 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-SSY$_{EV}$ relationship varied with sediment availability and erodibility in watersheds. Duvert et al. (2012) found that intercepts of the Qmax-SSY$_{EV}$ 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 SSY$_{EV}$-Qmax relationship ranged from 111-4,320 (Qmax in m³/s/km², SSY$_{EV}$ 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

34

735   among watersheds. In the watersheds in Duvert et al. (2012), slopes ranged from 0.95-1.82, and

736   from 1.06-2.45 in eighteen other watersheds (0.60-1,538 km²) in diverse geographical settings

737   (Basher et al., 1997; Fahey and Marden, 2000; Hicks et al., 2009; Rankl, 2004; Tropeano, 1991)

738   compiled by Duvert et al. (2012). In Faga'alu, slopes were 1.51 and 1.40 in the UPPER and

739   TOTAL Faga'alu watersheds, respectively, which are very consistent with the slopes presented in

740   Rankl (2004) and Duvert et al. (2012), despite large differences in climate and land cover.

741   In Faga'alu, SSY_{EV} was least correlated with the Erosivity Index (EI30). Duvert et al.

742   (2012) also found low correlation coefficients with 5 min rainfall intensity for 8 watersheds in

743   France and Mexico. Rodrigues et al. (2013) hypothesized that EI30 is poorly correlated with

744   SSY_{EV} due to the effect of previous events on antecedent moisture conditions and in-channel

745   sediment storage. Cox et al. (2006) found EI30 was more correlated with soil loss in an

746   agricultural watershed than a forested watershed, and Faga'alu is mainly covered in dense forest.

747   Similar to other studies (Basher et al., 2011; Duvert et al., 2012; Fahey et al., 2003; Hicks, 1990;

748   Rankl, 2004; Rodrigues et al., 2013) the highest correlations with SSY_{EV} at Faga'alu were

749   observed for discharge metrics. While Qsum and Psum had higher correlations in individual

750   watersheds, Qmax was a good predictor of SSY_{EV} in both the disturbed and undisturbed

751   watershed.

752   Comparing sSSY and SSC in other small Pacific Island watersheds

753   Sediment yield is highly variable among individual watersheds, but is generally

754   controlled by climate, vegetation cover, and geology, with human disturbance playing an

755   increasing role in the 20th century (Syvitski et al., 2005). Sediment yields in tropical Southeast

756   Asia and high-standing islands between Asia and Australia range from ~10 tons/km²/yr in the

757   granitic Malaysian Peninsula to ~10,000 tons/km²/yr in the tectonically active, steeply sloped

758　island of Papua New Guinea (Douglas, 1996). Sediment yields from Faga'alu are on the lower

759　end of the range, with sSSY of 45-68 tons/km²/yr from the undisturbed UPPER watershed, and

760　241-247 tons/km²/yr from the disturbed TOTAL watershed.

761　　　　Milliman and Syvitski (1992) report high average sSSY (1,000-3,000 tons/km²/yr) from

762　watersheds (10-100,000 km²) in tropical Asia and Oceania, though their regional models of sSSY

763　as a function of basin size and maximum elevation predict only 13 tons/km²/yr from watersheds

764　with peak elevation 500-1,000 m (highest point of UPPER Faga'alu subwatershed is 653 m), and

765　68 tons/km²/yr for max elevations of 1,000-3,000. Given the high vegetation cover and lack of

766　human activity in the UPPER Faga'alu subwatershed, its sSSY should be lower than sSSY from

767　watersheds presented in Milliman and Syvitski (1992), which included watersheds with human

768　disturbance. sSSY from the forested UPPER Faga'alu subwatershed (45-68 tons/km²/yr) was

769　approximately three to five times higher than the prediction from the Milliman and Syvitski

770　(1992) model (13 tons/km²/yr). The scatter around their model is large for smaller watersheds,

771　and the Faga'alu data fall within the range of scatter (Figures 5e and 6e in Milliman and Syvitski

772　(1992)).

773　　　　Sediment yield has been measured using modern fluvial measurements similar to ours for

774　two Hawaiian watersheds: Hanalei watershed on Kauai ("Hanalei"), and Kawela watershed on

775　Molokai ("Kawela") (Table 8) (Ferrier et al., 2013; Stock and Tribble, 2010). Hanalei (54 km²)

776　has steep relief and mean areal precipitation of 3,866 mm/yr (Ferrier et al., 2013), which is

777　slightly higher than rainfall at Faga'alu during the observation period (3,247 mm/yr). Over a four

778　year period, SSC at Hanalei averaged 63 mg/L and reached a maximum of 2,750 mg/L (Stock

779　and Tribble, 2010), which is slightly lower than observations at Faga'alu (mean 148 mg/L,

780　maximum 3,500 mg/L). Calhoun and Fletcher (1999) estimated sSSY from Hanalei as 140±55

781 tons/km²/yr, but had fewer data than Stock and Tribble (2010), who estimated sSSY as 525

782 tons/km²/yr. Ferrier et al., (2013) reported annual suspended sediment yield at Hanalei as 369 ±

783 114 tons/km²/yr. These values are all higher than observed at Faga'alu under both undisturbed

784 (45-68 tons/km²/yr) and disturbed (430-441 tons/km²/yr) subwatersheds. Rocks at Hanalei are of

785 similar age (1.5 Mya) or older (3.95-4.43 Mya) (Ferrier et al., 2013) compared with Faga'alu

786 (1.2 Mya) (McDougall, 1985), so landscape age does not explain the difference in observed SSY

787 between Hanalei and Faga'alu. Kawela (14 km²) is disturbed by grazing and is in a sub-humid

788 climate, where precipitation varies with elevation from 500-3,000 mm. Stock and Tribble (2010)

789 estimated sSSY from Kawela as 459 tons/km²/yr, which is similar to the disturbed subwatershed

790 in Faga'alu, but nearly twice as high as the TOTAL Faga'alu watershed. In Kawela, SSC (mean

791 3,490 mg/L, maximum 54,000 mg/L) was much higher than measured in Faga'alu TOTAL

792 watershed, so the difference in SSY is due in part to higher SSC rather than to higher observed

793 runoff. Overall, both Hawaiian watersheds have higher SSY than Faga'alu, which is consistent

794 with the low intercepts of Faga'alu in the Qmax-SSY$_{EV}$ relationships, and suggests that Faga'alu

795 may have uniquely low erosion rates for a steep volcanic watershed. Precipitation variability may

796 contribute to the difference in SSY, so a more thorough comparison between Hanalei and

797 Faga'alu would require a storm-wise analysis of the type performed here.

798   Annual sSSY from the quarry was estimated from Equation 6 to be approximately 2,800

799 tons/km²/yr. The quarry surfaces are comprised of haul roads, piles of overburden, and steep rock

800 faces which can be described as a mix of unpaved roads and cut-slopes. Literature values show

801 measured sSSY from cutslopes varying from 0.01 tons/km²/yr in Idaho (Megahan, 1980) to

802 105,000 tons/km²/yr in Papua New Guinea (Blong and Humphreys, 1982), so the sSSY ranges

803 measured in this study are well within the ranges found in the literature.

Comparison with other kinds of sediment disturbance

804

805   Other studies in small, mountainous watersheds have documented one to several orders

806 of magnitude increases in SSY from land use that disturbs a small fraction of the watershed area.

807 Urbanization and mining can increase sediment yield by two to three orders of magnitudes in

808 catchments of several km². Yields from construction sites can exceed those from the most

809 unstable, tectonically active natural environments of Southeast Asia (Douglas, 1996). In Kawela

810 watershed on Molokai, less than 5% of the land produces most of the sediment, and only 1%

811 produces ~50% of the sediment (Risk, 2014; Stock et al., 2010). In three basins on St. John, US

812 Virgin Islands unpaved roads increased sediment delivery rates by 3-9 times (Ramos-Scharrón

813 and Macdonald, 2005). Disturbances at larger scales have resulted in similar increases in total

814 SSY to coral environments. The development of the Great Barrier Reef (GBR) catchment

815 (423,000 km^2) since European settlement (ca.1830) led to increases in SSY by an estimated

816 factor of 5.5x (Kroon et al., 2012). Mining has been a major contributor of sediment in other

817 watersheds on volcanic islands with steep topography and high precipitation, increasing sediment

818 yields by 5-10 times in a watershed in Papua New Guinea (Hettler et al., 1997; Thomas et al.,

819 2003). In contrast to other land disturbances like fire, logging, or urbanization where sediment

820 disturbance decreases over time, the disturbance from mining is persistently high. Disturbance

821 magnitudes are similar to the construction phase of urbanization (Wolman and Schick, 1967), or

822 high-traffic unpaved roads (Reid and Dunne, 1984), but persist or even increase over time.

823   While unpaved roads are often identified as a source of sediment in humid forested

824 regions (Lewis et al., 2001; Ramos-Scharrón and Macdonald, 2005; Reid and Dunne, 1984),

825 field observations at Faga'alu suggested that most roads in the urban area were stabilized with

826 aggregate and not generating significant amounts of sediment. Other disturbances in Faga'alu

827 included a few small agricultural plots, small construction sites and bare dirt on roadsides.

828 Repeated surface disturbance at the quarry is a key process maintaining high rates of sediment

829 generation. Given the large distance to other sources of building material, aggregate mining and

830 associated sediment disturbance may be a critical sediment source on remote islands in the

831 Pacific and elsewhere.

832 Conclusion

833   Human disturbance has increased sediment yield to Faga'alu Bay by 3.9x over pre-

834 disturbance levels. The human-disturbed subwatershed accounted for the majority (87%) of total

835 sediment yield, and the quarry (1.1% of watershed area) contributed about a third of total SSY to

836 the Bay. Qmax was a good predictor of SSY_{EV} in both the disturbed and undisturbed watershed,

837 making it a promising predictor in diverse environments. The slopes of the Qmax-SSY_{EV}

838 relationships were comparable with other studies, but the model intercepts were an order of

839 magnitude lower than intercepts from watersheds in semi-arid to semi-humid climates. This

840 suggests that sediment availability is relatively low in the Faga'alu watershed, either because of

841 the heavy forest cover or volcanic rock type. The event-wise approach did not require continuous

842 in situ monitoring for a single or multiple years, which would not have been logistically possible

843 in this remote study area. This study presents an innovative method to combine sampling and

844 analysis strategies to measure sediment contributions from key sources, estimate baseline annual

845 sediment yields prior to management, and rapidly develop an empirical sediment yield model for

846 a remote, data-poor watershed.

Acknowledgements

References

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

867   Basher, L., Hicks, D., Clapp, B., Hewitt, T., 2011. Sediment yield response to large storm events

868   and forest harvesting, Motueka River, New Zealand. New Zeal. J. Mar. Freshw. Res. 45,

869   333–356. doi:10.1080/00288330.2011.570350

870   Basher, L.R., Hicks, D.M., Handyside, B., Ross, C.W., 1997. Erosion and sediment transport

871   from the market gardening lands at Pukekohe, Auckland, New Zealand. J. Hydrol. 36, 73–

872   95.

873   Bégin, C., Brooks, G., Larson, R. a., Dragićević, S., Ramos Scharrón, C.E., Coté, I.M., 2014.

874   Increased sediment loads over coral reefs in Saint Lucia in relation to land use change in

875   contributing watersheds. Ocean Coast. Manag. 95, 35–45.

876   doi:10.1016/j.ocecoaman.2014.03.018

877   Blong, R.J., Humphreys, G.S., 1982. Erosion of road batters in Chim Shale, Papua New Guinea.

878   Civ. Eng. Trans. Inst. Eng. Aust. CE24 1, 62–68.

879   Bonta, J. V, 2000. Impact of Coal Surface Mining and Reclamation on Suspended Sediment in

880   Three Ohio Watersheds. JAWRA J. Am. Water Resour. Assoc. 36, 869–887.

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

882   Buchanan-Banks, J., 1979. The October 28, 1979 Landslidng on Tutuila. Open File Report 81-

883   81. U.S. Geological Survey.

884 Calhoun, R.S., Fletcher, C.H., 1999. Measured and predicted sediment yield from a subtropical,

885   heavy rainfall, steep-sided river basin: Hanalei, Kauai, Hawaiian Islands. Geomorphology

886   30, 213–226.

887 Cox, C.A., Sarangi, A., Madramootoo, C.A., 2006. Effect of land management on runoff and soil

888   losses from two small watersheds in St Lucia. L. Degrad. Dev. 17, 55–72.

889   doi:10.1002/ldr.694

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

891   Pago Pago, American Samoa.

892 Curtis, S., Wetzell, L., Wiles, P., Tinitali, R., 2011. Turbidity in Faga'alu Stream: The Sources,

893   Impacts, and Solutions.

894 Daly, C., Halbleib, M., Smith, J.I., Gibson, W.P., Doggett, M.K., Taylor, G.H., Curtis, J.,

895   Passteris, P.P., 2008. Physiographically sensitive mapping of climatological temperature

896   and precipitation across the conterminous United States. Int. J. Climatol. 28, 2031.

897   doi:10.1002/joc

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

899   Hydropower.

900 Douglas, I., 1996. The impact of land-use changes, especially logging, shifting cultivation,

901   mining and urbanization on sediment yields in humid tropical Southeast Asia: A review

902   with special reference to Borneo. IAHS-AISH Publ. 236, 463–471.

903   Dunne, T., Leopold, L.B., 1978. Water in environmental planning. W.H. Freeman and Company,

904   New York.

905   Duvert, C., Gratiot, N., 2010. Construction of the stage-discharge rating curve and the SSC-

906   turbidity calibration curve in San Antonio Coapa 2009 hydrological season.

907   Duvert, C., Nord, G., Gratiot, N., Navratil, O., Nadal-Romero, E., Mathys, N., Némery, J.,

908   Regüés, D., García-Ruiz, J.M., Gallart, F., Esteves, M., 2012. Towards prediction of

909   suspended sediment yield from peak discharge in small erodible mountainous catchments

910   (0.45–22km2) of France, Mexico and Spain. J. Hydrol. 454-455, 42–55.

911   doi:10.1016/j.jhydrol.2012.05.048

912   Eyre, P.R., 1989. Ground-water quality reconnaissance, Tutuila, American Samoa, U.S.

913   Geological Survey Water Resources Investigations Report 94-4142. Honolulu, HI.

914   Fabricius, K.E., 2005. Effects of terrestrial runoff on the ecology of corals and coral reefs:

915   review and synthesis. Mar. Pollut. Bull. 50, 125–46. doi:10.1016/j.marpolbul.2004.11.028

916   Fahey, B.D., Marden, M., 2000. Sediment yields from a forested and a pasture catchment,

917   coastal Hawke's Bay, North Island, New Zealand. J. Hydrol. 39, 49–63.

918   Fahey, B.D., Marden, M., Phillips, C.J., 2003. Sediment yields from plantation forestry and

919   pastoral farming, coastal Hawke's Bay, North Island, New Zealand. J. Hydrol. 42, 27–38.

920   Fenner, D., Speicher, M., Gulick, S., Aeby, G., Aletto, S.C., Anderson, P., Carroll, B.P.,

921   DiDonato, E.M., DiDonato, G.T., Farmer, V., Fenner, D., Gove, J., Gulick, S., Houk, P.,

922   Lundblad, E., Nadon, M., Riolo, F., Sabater, M.G., Schroeder, R., Smith, E., Speicher, M.,

923   Tuitele, C., Tagarino, A., Vaitautolu, S., Vaoli, E., Vargas-angel, B., Vroom, P., 2008. The

924   State of Coral Reef Ecosystems of American Samoa, in: The State of Coral Reef

925   Ecosystems of the United States and Pacific Freely Associated States. pp. 307–351.

926   Ferrier, K.L., Taylor Perron, J., Mukhopadhyay, S., Rosener, M., Stock, J.D., Huppert, K.L.,

927   Slosberg, M., 2013. Covariation of climate and long-term erosion rates across a steep

928   rainfall gradient on the Hawaiian island of Kaua'i. Bull. Geol. Soc. Am. 125, 1146–1163.

929   doi:10.1130/B30726.1

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

931   Gellis, A.C., 2013. Factors influencing storm-generated suspended-sediment concentrations and

932   loads in four basins of contrasting land use, humid-tropical Puerto Rico. Catena 104, 39–57.

933   doi:10.1016/j.catena.2012.10.018

934   Gippel, C.J., 1995. Potential of turbidity monitoring for measuring the transport of suspended

935   solids in streams. Hydrol. Process. 9, 83–97.

936   Gomi, T., Moore, R.D., Hassan, M.A., 2005. Suspended sediment dynamics in small forest

937   streams of the Pacific Northwest. J. Am. Water Resour. Assoc.

938   Gray, J.R., 2014. Measuring Suspended Sediment, in: Ahuja, S. (Ed.), Comprehensive Water

939   Quality and Purification. Elsevier, pp. 157–204. doi:10.1016/B978-0-12-382182-9.00012-8

940   Gray, J.R., Glysson, G.D., Turcios, L.M., Schwarz, G.E., 2000. Comparability of Suspended-

941   Sediment Concentration and Total Suspended Solids Data U.S. Geological Survey Water-

942   Resources Investigations Report 00-4191. Reston, Va.

943   Harmel, R.D., Cooper, R.J., Slade, R.M., Haney, R.L., Arnold, J.G., 2006. Cumulative

944   uncertainty in measured streamflow and water quality data for small watersheds. Trans.

945   Am. Soc. Agric. Biol. Eng. 49, 689–701.

946   Harmel, R.D., Smith, D.R., King, K.W., Slade, R.M., 2009. Estimating storm discharge and

947   water quality data uncertainty: A software tool for monitoring and modeling applications.

948   Environ. Model. Softw. 24, 832–842.

949   Harrelson, C.C., Rawlins, C.L., Potyondy, J.P., 1994. Stream channel reference sites: an

950   illustrated guide to field technique. USDA Forest Service General Technical Report RM-

951   245. US Department of Agriculture, Fort Collins, CO.

952   Henderson, G.W., Toews, D.A.A., 2001. Using Sediment Budgets to Test the Watershed

953   Assessment Procedure in Southeastern British Columbia, in: Toews, D.A.A., Chatwin, S.

954   (Eds.), Watershed Assessment in the Southern Interior of British Columbia. B.C. Ministry

955   of Forests, Research Branch, Victoria, British Columbia, pp. 189–208.

956   Hettler, J., Irion, G., Lehmann, B., 1997. Environmental impact of mining waste disposal on a

957   tropical lowland river system: a case study on the Ok Tedi Mine, Papua New Guinea.

958   Miner. Depos. 32, 280–291. doi:10.1007/s001260050093

959   Hicks, D.M., 1990. Suspended sediment yields from pasture and exotic forest basins, in:

960   Proceedings of the New-Zealand Hydrological Society Symposium. Auckland, New

961   Zealand.

962   Hicks, D.M., Hoyle, J., Roulston, H., 2009. Analysis of sediment yields within Auckland region.

963   ARC Technical Report 2009/064. Prepared by NIWA for Auckland Regional Council.

964   Holst-Rice, S., Messina, A., Biggs, T.W., Vargas-Angel, B., Whitall, D., 2015. Baseline

965   Assessment of Faga'alu Watershed: A Ridge to Reef Assessment in Support of Sediment

966   Reduction Activities. NOAA Coral Reef Conservation Program, Silver Spring, MD.

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

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

969   Izuka, S.K., Giambelluca, T.W., Nullet, M.A., 2005. Potential Evapotranspiration on Tutuila ,

970   American Samoa. U.S. Geological Survey Scientific Investigations Report 2005-5200.

971   Kearns, R., 2013. Personal Communication.

972   Kinnell, P.I.A., 2013. Modelling event soil losses using the Q R EI 30 index within RUSLE2.

973   Hydrol. Process. doi:10.1002/hyp

974   Kroon, F.J., Kuhnert, P.M., Henderson, B.L., Wilkinson, S.N., Kinsey-Henderson, A., Abbott,

975   B., Brodie, J.E., Turner, R.D.R., 2012. River loads of suspended solids, nitrogen,

976   phosphorus and herbicides delivered to the Great Barrier Reef lagoon. Mar. Pollut. Bull. 65,

977   167–81. doi:10.1016/j.marpolbul.2011.10.018

978   Latinis, D.K., Moore, J., Kennedy, J., 1996. Archaeological Survey and Investigations

979   Conducted at the Faga'alu Quarry, Ma'oputasi County, Tutuila, American Samoa, February

980   1996: Prepared for George Poysky, Sr., Samoa Maritime, PO Box 418, Pago Pago,

981   American Samoa, 96799. Archaeological Consultants of the Pacific Inc., 59-624 Pupukea

982   Rd., Haleiwa, HI 96712.

983   Lewis, J., 1996. Turbidity-controlled suspended sediment sampling for runoff-event load

984   estimation. Water Resour. Res. 32, 2299–2310.

985   Lewis, J., Mori, S.R., Keppeler, E.T., Ziemer, R.R., 2001. Impacts of Logging on Storm Peak

986   Flows , Flow Volumes and Suspended Sediment Loads in Caspar Creek, CA, in: Land Use

987   and Watersheds: Human Influence on Hydrology and Geomorphology in Urban and Forest

988   Areas. pp. 1–76.

989   McDougall, I., 1985. Age and Evolution of the Volcanoes of Tutuila American Samoa. Pacific

990   Sci. 39, 311–320.

991   Megahan, W.F., 1980. Erosion from roadcuts in granitic slopes of the Idaho Batholith, in:

992   Proceedings Cordilleran Sections of the Geological Society of America, 76th Annual

993   Meeting. Oregon State University, Corvallis, OR, p. 120.

994   Megahan, W.F., Wilson, M., Monsen, S.B., 2001. Sediment production from granitic cutslopes

995   on forest roads in Idaho, USA. Earth Surf. Process. Landforms 26, 153–163.

996   Menking, J. a., Han, J., Gasparini, N.M., Johnson, J.P.L., 2013. The effects of precipitation

997   gradients on river profile evolution on the Big Island of Hawai'i. Bull. Geol. Soc. Am. 125,

998   594–608. doi:10.1130/B30625.1

999   Milliman, J.D., Syvitski, J.P.M., 1992. Geomorphic/tectonic control of sediment discharge to the

1000   ocean: the importance of small mountainous rivers. J. Geol. 100, 525–544.

1001   Nakamura, S., 1984. Soil Survey of American Samoa. US Department of Agriculture Soil

1002   Conservation Service, Pago Pago, American Samoa.

1003   Nathan, R.J., McMahon, T. a, 1990. Evaluation of Automated Techniques for Base Flow and

1004   Recession Analyses. Water Resour. Res. 26, 1465–1473. doi:10.1029/WR026i007p01465

1005   Nearing, M. a, Nichols, M.H., Stone, J.J., Renard, K.G., Simanton, J.R., 2007. Sediment yields

1006   from unit-source semiarid watersheds at Walnut Gulch. Water Resour. Res. 43, 1–10.

1007   doi:10.1029/2006WR005692

1008   NOAA's Ocean Service, Coastal Services Center, 2010. 2010 C-CAP Land Cover, Territory of

1009   American Samoa, Tutuila.

1010   Perreault, J., 2010. Development of a Water Budget in a Tropical Setting Accounting for

1011   Mountain Front Recharge: Tutuila, American Samoa. University of Hawai'i.

1012   Perroy, R.L., Bookhagen, B., Chadwick, O. a., Howarth, J.T., 2012. Holocene and Anthropocene

1013   Landscape Change: Arroyo Formation on Santa Cruz Island, California. Ann. Assoc. Am.

1014   Geogr. 102, 1229–1250. doi:10.1080/00045608.2012.715054

1015   Ramos-Scharrón, C.E., Macdonald, L.H., 2005. Measurement and prediction of sediment

1016   production from unpaved roads, St John, US Virgin Islands. Earth Surf. Process. Landforms

1017   30, 1283–1304.

1018   Ramos-Scharrón, C.E., Macdonald, L.H., 2007. Measurement and prediction of natural and

1019   anthropogenic sediment sources, St. John, US Virgin Islands. Catena 71, 250–266.

1020   Rankl, J.G., 2004. Relations Between Total-Sediment Load and Peak Discharge for Rainstorm

1021   Runoff on Five Ephemeral Streams in Wyoming. U.S. Geological Survey Water-Resources

1022   Investigations Report 02-4150. Denver, CO.

1023   Rapp, A., 1960. Recent development of mountain slopes in Karkevagge and surroundings,

1024   northern Scandinavia. Geogr. Ann. 42, 65–200.

1025   Reid, L.M., Dunne, T., 1984. Sediment production from forest road surfaces. Water Resour. Res.

1026   20, 1753–1761.

1027   Reid, L.M., Dunne, T., 1996. Rapid evaluation of sediment budgets. Catena Verlag, Reiskirchen,

1028   Germany.

1029   Risk, M.J., 2014. Assessing the effects of sediments and nutrients on coral reefs. Curr. Opin.

1030   Environ. Sustain. 7, 108–117. doi:10.1016/j.cosust.2014.01.003

1031   Rodrigues, J.O., Andrade, E.M., Ribeiro, L.A., 2013. Sediment loss in semiarid small watershed

1032   due to the land use. Rev. Ciência Agronômica 44, 488–498.

1033   Sadeghi, S.H.R., Mizuyama, T., Miyata, S., Gomi, T., Kosugi, K., Mizugaki, S., Onda, Y., 2007.

1034   Is MUSLE apt to small steeply reforested watershed? J. For. Res. 12, 270–277.

1035   doi:10.1007/s10310-007-0017-9

1036   Slaymaker, O., 2003. The sediment budget as conceptual framework and management tool.

1037   Hydrobiologia 494, 71–82.

1038   Stock, J.D., Rosener, M., Schmidt, K.M., Hanshaw, M.N., Brooks, B.A., Tribble, G., Jacobi, J.,

1039   2010. Sediment budget for a polluted Hawaiian reef using hillslope monitoring and process

1040   mapping, in: American Geophysical Union Fall Meeting. p. #EP22A–01.

1041   Stock, J.D., Tribble, G., 2010. Erosion and sediment loads from two Hawaiian watersheds, in:

1042   2nd Joint Federal Interagency Conference. Las Vegas, NV.

1043   Storlazzi, C.D., Norris, B.K., Rosenberger, K.J., 2015. The influence of grain size, grain color,

1044   and suspended-sediment concentration on light attenuation: Why fine-grained terrestrial

1045   sediment is bad for coral reef ecosystems. Coral Reefs 34, 967–975. doi:10.1007/s00338-

1046   015-1268-0

1047   Syvitski, J.P.M., Vörösmarty, C.J., Kettner, A.J., Green, P., 2005. Impact of humans on the flux

1048   of terrestrial sediment to the global coastal ocean. Science (80-.). 308, 376–380.

1049   doi:10.1126/science.1109454

1050   Thomas, S., Ridd, P. V, Day, G., 2003. Turbidity regimes over fringing coral reefs near a mining

1051   site at Lihir Island, Papua New Guinea. Mar. Pollut. Bull. 46, 1006–14. doi:10.1016/S0025-

1052   326X(03)00122-X

1053   Tonkin & Taylor International Ltd., 1989. Hydropower feasibility studies interim report - Phase

1054   1. Ref: 97/10163.

1055   Topping, J., 1972. Errors of Observation and their Treatment, 4th ed. Chapman and Hall,

1056   London, UK.

1057   Tropeano, D., 1991. High flow events, sediment transport in a small streams in the "Tertiary

1058   Basin" area in Piedmont (northwest Italy). Earth Surf. Process. Landforms 16, 323–339.

1059   Turnipseed, D.P., Sauer, V.B., 2010. Discharge Measurements at Gaging Stations, in: U.S.

1060   Geological Survey Techniques and Methods Book 3, Chap. A8. Reston, Va., p. 87.

1061   URS Company, 1978. American Samoa Water Resources Study: Assessment of Water Systems

1062   American Samoa. Coastal Zone Information Center, Honolulu, HI.

1063   Walling, D.E., 1977. Assessing the accuracy of suspended sediment rating curves for a small

1064   basin. Water Resour. Res. 13, 531–538.

1065   Walling, D.E., 1999. Linking land use, erosion and sediment yields in river basins.

1066   Hydrobiologia 410, 223–240.

1067   Walling, D.E., Collins, a. L., 2008. The catchment sediment budget as a management tool.

1068   Environ. Sci. Policy 11, 136–143. doi:10.1016/j.envsci.2007.10.004

1069   Wemple, B.C., Jones, J.A., Grant, G.E., 1996. Channel Network Extension by Logging Roads in

1070   Two Basins, Western Cascades, Oregon. Water Resour. Bull. 32, 1195–1207.

1071 West, K., van Woesik, R., 2001. Spatial and temporal variance of river discharge on Okinawa

1072   (Japan): inferring the temporal impact on adjacent coral reefs. Mar. Pollut. Bull. 42, 864–

1073   72.

1074 Wolman, M.G., Schick, A.P., 1967. Effects of construction on fluvial sediment, urban and

1075   suburban areas of Maryland. Water Resour. Res. 3, 451–464.

1076 Wong, M., 1996. Analysis of Streamflow Characteristics for Streams on the Island of Tutuila,

1077   American Samoa. U.S. Geological Survey Water-Resources Investigations Report 95-4185.

1078 Wulf, H., Bookhagen, B., Scherler, D., 2012. Climatic and geologic controls on suspended

1079   sediment flux in the Sutlej River Valley, western Himalaya. Hydrol. Earth Syst. Sci. 16,

1080   2193–2217. doi:10.5194/hess-16-2193-2012

1081 Zimmermann, A., Francke, T., Elsenbeer, H., 2012. Forests and erosion: Insights from a study of

1082   suspended-sediment dynamics in an overland flow-prone rainforest catchment. J. Hydrol.

1083   170–181.

1084

APPENDIX 1. Dams in Faga'alu watershed

1086   Faga'alu stream was dammed at 4 locations above the village: 1) Matafao Dam (elevation

1087   244 m) near the base of Mt. Matafao, draining 0.20 km², 2) Vaitanoa Dam at Virgin Falls

1088   (elevation 140 m), draining an additional 0.44 km², 3) a small unnamed dam below Vaitanoa

1089   Dam at elevation 100m, and 4) Lower Faga'alu Dam (elevation 48 m), immediately upstream of

1090   a large waterfall 30 m upstream of the quarry, draining an additional 0.26 km² (Tonkin & Taylor

1091   International Ltd., 1989). A 2012 aerial LiDAR survey (Photo Science, Inc.) indicates the

1092   drainage area at the Lower Faga'alu Dam is 0.90 km². A small stream capture/reservoir (~35 m³)

1093   is also present on a side tributary that joins Faga'alu stream on the south bank, opposite the

1094   quarry. It is connected to a ~6 cm diameter pipe but it is unknown when or by whom it was built,

1095   its initial capacity, or if it is still conveying water. During all site visits water was overtopping

1096   this small structure through the spillway crest, suggesting it is fed by a perennial stream.

1097   Matafao Dam was constructed in 1917 for water supply to the Pago Pago Navy base,

1098   impounding a reservoir with initial capacity of 1.7 million gallons (6,400 m³) and piping the flow

1099   out of the watershed to a hydropower and water filtration plant in Fagatogo. In the early 1940's

1100   the Navy replaced the original cement tube pipeline and hydropower house with cast iron pipe

1101   but it is unknown when the scheme fell out of use (Tonkin & Taylor International Ltd., 1989;

1102   URS Company, 1978). Remote sensing and a site visit on 6/21/13 confirmed the reservoir is still

1103   filling to the spillway crest with water and routing some flow to the Fagatogo site, though the

1104   amount is much less than the 10 in. diameter pipes conveyance capacity and the flow rate

1105   variability is unknown. A previous site visit on 2/21/13 by American Samoa Power Authority

1106   (ASPA) found the reservoir empty of water but filled with an estimated 3-5 meters of fine

1107   sediment (Kearns, 2013). Interviews with local maintenance staff and historical photos

1108 confirmed the Matafao Reservoir was actively maintained and cleaned of sediment until the early

1109 70's.

1110   The Vaitanoa (Virgin Falls) Dam, was built in 1964 to provide drinking water but the

1111 pipe was not completed as of 10/19/89, and a stockpile of some 40 (8 ft. length) 8 in. diameter

1112 asbestos-cement pipes was found on the streambanks. Local quarry staff recall the pipes were

1113 removed from the site sometime in the 1990's. The Vaitanoa Reservoir had a design volume of

1114 4.5 million gallons (17,000m³), but is assumed to be full of sediment since the drainage valves

1115 were never opened and the reservoir was overtopping the spillway as of 10/18/89 (Tonkin &

1116 Taylor International Ltd., 1989). A low masonry weir was also constructed downstream of the

1117 Vaitanoa Dam, but not connected to any piping.

1118   The Lower Faga'alu Dam was constructed in 1966/67 just above the Samoa Maritime,

1119 Ltd. Quarry, as a source of water for the LBJ Medical Centre. It is unknown when this dam went

1120 out of use but in 1989 the 8 in. conveyance pipe was badly leaking and presumed out of service.

1121 The 8 in. pipe disappears below the floor of the Samoa Maritime quarry and it is unknown if it is

1122 still conveying water or has plugged with sediment. The derelict filtration plant at the entrance to

1123 the quarry was disconnected prior to 1989 (Tonkin & Taylor International Ltd., 1989). The

1124 original capacity was 0.03 million gallons (114 m³) but is now full of coarse sediment up to the

1125 spillway crest. No reports were found indicating this structure was ever emptied of sediment.

1126 APPENDIX 2. Stream gaging in Faga'alu Watershed

1127   Stream gaging sites were chosen to take advantage of an existing control structure at FG1

1128 (Figure A2.1) and a stabilized stream cross section at FG3 (Figure A2.2)(Duvert and Gratiot,

1129 2010). At FG1 and FG3, Q was calculated from 15 minute interval stream stage measurements,

1130 using a stage-Q rating curve calibrated to manual Q measurements made under baseflow and

1131   stormflow conditions (Figures A2.3 and A2.4). Stream stage was measured with non-vented

1132   pressure transducers (PT) (Solinst Levelogger or Onset HOBO Water Level Logger) installed in

1133   stilling wells at FG1 and FG3. Barometric pressure data collected at Wx were used to calculate

1134   stage from the pressure data recorded by the PT. Data gaps in barometric pressure from Wx were

1135   filled by data from stations at Pago Pago Harbor (NSTP6) and NOAA Climate Observatory at

1136   Tula (TULA) (Figure 1). Priority was given to the station closest to the watershed with valid

1137   barometric pressure data. Barometric data were highly correlated and the data source made little

1138   (<1cm) difference in the resulting water level. Q was measured in the field by the area-velocity

1139   method (AV) using a Marsh-McBirney flowmeter to measure flow velocity and channel surveys

1140   measure cross-sectional area (Harrelson et al., 1994; Turnipseed and Sauer, 2010).

1141   AV-Q measurements could not be made at high stages at FG1 and FG3 for safety

1142   reasons, so stage-Q relationships were constructed to estimate a continuous record of Q. At FG3,

1143   the channel is rectangular with stabilized rip-rap on the banks and bed (Figure A2.2). Recorded

1144   stage varied from 4 to 147 cm. AV-Q measurements (n= 14) were made from 30 to 1,558.0

1145   L/sec, covering a range of stages from 6 to 39 cm. The highest recorded stage was much higher

1146   than the highest stage with measured Q so the rating could not be extrapolated by a power law.

1147   Stream conditions at FG3 fit the assumption for Manning's equation, so the stage-Q rating at

1148   FG3 was created using Manning's equation, calibrating Manning's n (0.067) to the Q

1149   measurements (Figure A2.3).

1150   At FG1, the flow control structure is a masonry ogee spillway crest of a defunct stream

1151   capture. The structure is a rectangular channel 43 cm deep that transitions abruptly to gently

1152   sloping banks, causing an abrupt change in the stage-Q relationship (Figure A2.1). At FG1,

1153   recorded stage height ranged from 4 to 120 cm, while area-velocity Q measurements (n= 22)

1154 covered stages from 6 to 17 cm. Since the highest recorded stage (120 cm) was higher than the

1155 highest stage with measured Q (17 cm), and there was a distinct change in channel geometry

1156 above 43 cm the rating could not be extrapolated by a power law. The flow structure did not

1157 meet the assumptions for using Manning's equation to predict flow so the HEC-RAS model was

1158 used (Brunner, 2010). The surveyed geometry of the upstream channel and flow structure at FG1

1159 were input to HEC-RAS, and the HEC-RAS model was calibrated to the Q measurements

1160 (Figure A2.4). While a power function fit Q measurements better than HEC-RAS for low flow,

1161 HEC-RAS fit better for Q above the storm threshold used in analyses of SSY (Figure A2.4).

1162 APPENDIX 3. Water discharge during storm events

1163 Insert Table A3.1 here

1164 APPENDIX 4. Turbidity-Suspended Sediment Concentration rating curves for turbidimeters

1165 in Faga'alu

1166 Turbidity (T) was measured at FG1 and FG3 using three types of turbidimeters: 1)

1167 Greenspan TS3000 (TS), 2) YSI 600OMS with 6136 turbidity probe (YSI), and 3) Campbell

1168 Scientific OBS500 (OBS). All turbidimeters were permanently installed in protective PVC

1169 housings near the streambed where the turbidity probe would be submerged at all flow

1170 conditions, with the turbidity probe oriented downstream. Despite regular maintenance, debris

1171 fouling during storm and baseflows was common and caused data loss during several storm

1172 events. Storm events with incomplete or invalid T data were not used in the analysis. A three-

1173 point calibration was performed on the YSI turbidimeter with YSI turbidity standards (0, 126,

1174 and 1000 NTU) at the beginning of each field season and approximately every 3-6 months

1175 during data collection. Turbidity measured with 0, 126, and 1000 NTU standards differed by less

1176   than 10% (4-8%) during each recalibration. The OBS requires calibration every two years, so

1177   recalibration was not needed during the study period. All turbidimeters were cleaned following

1178   storms to ensure proper operation.

1179   At FG3, a YSI turbidimeter recorded T (NTU) at 5 min intervals from January 30, 2012,

1180   to February 20, 2012, and at 15 min intervals from February 27, 2012 to May 23, 2012, when it

1181   was damaged during a large storm. The YSI turbidimeter was replaced with an OBS, which

1182   recorded Backscatter (BS) and Sidescatter (SS) at 5 min intervals from March 7, 2013, to July

1183   15, 2014 (OBSa), and was resampled to 15 min intervals. No data was recorded from August

1184   2013-January 2014 when the wiper clogged with sediment. A new OBS was installed at FG3

1185   from January, 2014, to August, 2014 (OBSb). To correct for some periods of high noise

1186   observed in the BS and SS data recorded by the OBSa in 2013, the OBSb installed in 2014 was

1187   programmed to make a burst of 100 BS and SS measurements at 15 min intervals, and record

1188   Median, Mean, STD, Min, and Max. All BS and SS parameters were analyzed to determine

1189   which showed the best relationship with SSC. Mean SS showed the highest r^2 and is a physically

1190   comparable measurement to NTU measured by the YSI and TS (Anderson, 2005).

1191   At FG1, the TS turbidimeter recorded T (NTU) at 5 min intervals from January 2012

1192   until it was vandalized and destroyed in July 2012. The YSI turbidimeter, previously deployed at

1193   FG3 in 2012, was repaired and redeployed at FG1 and recorded T (NTU) at 5 min intervals from

1194   June 2013 to October 2013, and January 2014 to August 2014. T data was resampled to 15 min

1195   intervals to compare with SSC samples for the T-SSC relationship, and to correspond to Q for

1196   calculating SSY.

1197   The T-SSC relationship can be unique to each region, stream, instrument or even each

1198   storm event (Lewis et al., 2001), and can be influenced by water color, dissolved solids and

1199   organic matter, temperature, and the shape, size, and composition of sediment. However, T has

1200   proved to be a robust surrogate measure of SSC in streams (Gippel, 1995), and is most accurate

1201   when a unique T-SSC relationship is developed for each instrument separately, using in situ grab

1202   samples under storm conditions (Lewis, 1996). A unique T-SSC relationship was developed for

1203   each turbidimeter, at each location, using 15 min interval T data and SSC samples from storm

1204   periods only (Figure A4.1). A "synthetic" T-SSC relationship was also developed by placing the

1205   turbidimeter in a black tub with water, and sampling T and SSC as sediment was added (Figure

1206   4.2), but results were not comparable to T-SSC relationships developed under actual storm

1207   conditions and were not used in further analyses.

1208   The T-SSC relationships varied among sampling sites and sensors but all showed

1209   acceptable r^2 values (0.79-0.99). Lower scatter was achieved by using grab samples collected

1210   during stormflows only. For the TS (not shown) and YSI deployed at FG1, the r2 values were

1211   high (0.58, 0.99) but the ranges of T and SSC values used to develop the relationships were

1212   considered too small (0-16 NTU) compared to the maximum observed during the deployment

1213   period (1,077 NTU) to develop a robust relationship for higher T values. Instead, the T-SSC

1214   relationship developed for the YSI turbidimeter installed at FG3 (Figure A4.1a) was used to

1215   calculate SSC from T data collected by the TS and the YSI at FG1. For the YSI turbidimeter,

1216   more scatter was observed in the T-SSC relationship at FG3 than at FG1 (Figure A4.1a), which

1217   could be attributed to the higher number and wider range of values sampled, and to temporal

1218   variability in sediment characteristics. The OBSa and OBSb turbidimeters had high r2 values

1219   (0.82, 0.93) and compared well between the two periods of deployment (Figure A4.1b).