Elsevier Editorial System(tm) for Journal of Hydrology
Manuscript Draft

Manuscript Number: HYDROL20966R2

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

Article Type: Research Paper

Keywords: Sediment yield, volcanic islands, land use, storm events, coastal sediment yield, American Samoa

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Abstract: Suspended sediment concentrations (SSC) and yields (SSY) during storm and non-storm periods, 2012-2014, were measured from undisturbed and human-disturbed portions of a small (1.8 km^2), mountainous watershed that drains to a sediment-stressed coral reef. Event-wise SSY (SSYEV) was calculated for 142 storms from measurements of water discharge (Q), turbidity (T), and SSC measured downstream of three key sediment sources: undisturbed forest, an aggregate quarry, and a village. SSC and SSYEV were significantly higher downstream of the quarry during both storm- and non-storm periods. The human-disturbed subwatershed (10.1% disturbed) accounted for an average of 87% of SSYEV from the watershed. Observed sediment yield (mass) to the coast, including human disturbed subwatersheds, was 3.9x the natural background. Specific SSY (mass/area) from the disturbed quarry area was 49x higher than from natural forest compared with 8x higher from the village area. Similar to mountainous watersheds in semi-arid and temperate climates, SSYEV from both the undisturbed and disturbed watersheds correlated closely with maximum event discharge (Qmax), event total precipitation and event total Q, but not with the Erosivity Index. Best estimates of annual SSY varied by method, from 45-143 tons/km^2/yr from the undisturbed subwatershed, 441-598 tons/km^2/yr from the human-disturbed subwatershed, and 241-368 tons/km2/yr from the total watershed. Sediment yield was very sensitive to disturbance; the quarry covers 1.1% of the total watershed area, but contributed 36% of SSYEV. Given the limited access to gravel for infrastructure development, sediment disturbance from local aggregate mining may be a critical sediment source on remote islands in the Pacific and elsewhere. Identification of erosion hotspots like the quarry using rapid, event-wise measures of suspended sediment yield will help efforts to mitigate sediment stress and restore coral reefs.

Response to Reviewers:

***Highlights (3 to 5 bullet points (maximum 85 characters including spaces per bullet point)**

- Human disturbance increased suspended sediment yield to Faga'alu Bay by 3.9x
- Maximum event discharge was a good predictor of storm suspended sediment yield
- Rapidly developed an empirical suspended sediment yield model for remote watershed

Comments from the Editor (EC) for Moderate Revisions, prior to sending out to Reviewers 1 (R1) and 2 (R2):

EC1) Please don't use abbreviations (e.g., SSY) in the highlights, please expand in full. As you have 2 highlights spare this should be OK.
Done.
Common abbreviations were used to keep under the limit of 85 characters, including spaces. They have been rewritten.

EC2) L38 (and elsewhere), can you please number all heading, sub-headings etc.? This will enable reviewers to more easily navigate your manuscript when they are reviewing it.
Done.
My mistake leaving these out.

EC3) L128, rather than have 'questions addressed' it would be preferable to have specific objectives or aims for your study. In the last paragraph of your Introduction can you please explicitly state what your 'aim(s)' or 'objective(s)' or 'hypothesis (hypotheses)' is (are)? That is, specifically use one of these words. While you have a purpose, this is a little broader than having specific aims or objectives. Consider using a bulleted sentence structure to list these. Note the word 'question' is used in the following to generically mean aim / objective / hypothesis. It is common practice to list the aims/objectives at the very end of the last paragraph of the Introduction section.

Note the grammar of such a sentence follows (please pay careful attention to the use of colons and semi-colons):
(i) question 1 is interesting;
(ii) question 2 is really interesting; and
(iii) my Mum thought I should write something about question 3.

Implementing this point makes it much easier for scientists from all language backgrounds to easily understand what you aim to do. This dove-tails into the comment directly below.
Done.
The word “Objectives” has been inserted to describe the numbered items in the last paragraph of the Introduction that summarize the two main objectives of the study.

We feel it is critical to explicitly state the research questions that the paper seeks to answer, as questions ending with a question mark. These questions are explicitly answered later in Results and Discussion, demonstrating that we have learned something about this hydrological system and our hypotheses were confirmed or not. We state the objectives of the data analysis (to quantify and model sediment yield) but more importantly we pose the questions that motivate this analysis, and structure key take-away messages of the paper.

EC4) Improved structure: once you've explicitly used one the following words to state what your 'aim(s)' or 'objective(s)' or 'hypothesis (hypotheses)' is (are), then, assuming you have objectives, use these objectives to provide structure to your revised MS. For example, let's assume you have three objectives, then use them to structure your Methods section, Results section and Discussion sections, as follows.
1 Introduction
2 Study Site and Materials (have as many sub-headings as needed to introduce all the datasets used, their pre-processing - or maybe this needs to be 2 main headings, noting you might also need a "2 Theoretical Background" section too, in which case this would heading #3, and all others would increment by 1)
3 Methods
    3.1 Objective 1 (4-8 words to summarise objective 1)
    3.2 Objective 2 (4-8 words to summarise objective 2)
    3.3 Objective 3 (and so on)
4 Results
    4.1 Objective 1 (same words as 3.1)
    4.2 Objective 2 (same words as 3.2 and so on)
    4.3 Objective 3
5 Discussion
    5.1 Objective 1
    5.2 Objective 2
    5.3 Objective 3

6 Conclusion

Currently I'm up to page 16 and given your structure and possible lack of numbered heading, I'm finding it very challenging to know what section of the (rather long) manuscript I'm reading.

Using the aims/objectives at end of your Introduction section to structure the rest of the paper makes it easy to read (and review).
Done.
The manuscript has been significantly shortened, and reorganized following the above template

EC5) L178, units of annual potential evapotranspiration need to be mm/yr, as you have correctly provided for the mean annual precipitation a few lines earlier.
Done.

EC6) As the JoH Guide for Authors is currently being updated and does not state the following can you please implement? Can you please provide all Figures in a WORD document with the figure captions directly following each figure? This means a reviewer only has to flick back-n-forth between 2 pages (text and figure).
Done.
The JoH and Elsevier Guide for Authors specifically calls for Figures and Tables to be submitted as separate files, with Figure Captions in separate document. This procedure required a fair bit of time to accomplish using the online submission system.

However, in the interest of making the review process as easy as possible, we have also compiled a new document including all figures, followed by the caption.

EC7) Plus you may wish to embed your figures and tables (and their captions) into the text directly following the paragraph where they are first mentioned. This will make it even easier for a reviewer. If you don't do this please put
< Figure 1 here please >
< Table 1 here please >
on new lines to highlight to reviewers (and the layout people) where the non-text elements should be located.
Done.
We added these tags in the appropriate places in the manuscript text, in addition to compiling a document with figures and captions, and uploading separately. We did not choose to embed figures in the text.

EC8) L749, what discharge metrics? It seems there is at least 1 word missing from this sentence.
Revised text:
Similar to other studies the highest correlations with SSY_{EV} at Faga'alu were observed for discharge metrics Qsum and Qmax (Basher et al., 2011; Duvert et al., 2012; Fahey et al., 2003; Hicks, 1990; Rankl, 2004; Rodrigues et al., 2013).

EC9) The submitted manuscript is long, very long. The PDF I see has 87 pages - that is big bordering on huge. As I've noticed that long manuscripts usually suffer harsh reviews I strongly urge you to seek to reduce the length of the submitted manuscript.
Can you move the Appendices into the Supplementary Material? If you can reduce the PDF that reviewers download to be 45 to 55 pages your manuscript will be much less likely to put reviewers offside from the start.

Appendices have been moved to Supplementary Material. We wanted to include these additional materials for an interested reviewer but they can be moved wherever you think is best. The manuscript text has also been shortened significantly.

This, and EC4, are the reasons I'm requesting moderate revision, as opposed to minor revision, as positively implementing these will take some time, however, it will be worth it as your manuscript will be clearer and much more likely to be viewed favourably by JoH reviewers.

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COMMENTS FROM EDITORS AND REVIEWERS

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Editor Comments:

1) Thanks for making improvements as requested by my pre-screening of your original submission.

No problem, thank you for taking the time to provide constructive reviews for improving the paper

2) Both reviewers in their confidential comments to me stated they thought the MS was too long. Assuming this MS is ultimately published in JoH, if a paper is too long it will not receive the attention it deserves, both you and the JoH do not want that. Once you've addressed all reviewer comments go through the revised MS with a fine tooth comb and critically ask yourself is this sentence needed and/or can it be tightened to reduce the overall word count. Please let me know how many words were contained the version the assessed by the reviewers, and how many words the next iteration is. Please also calculate a percentage reduction (if possible, if you can reduce it by 15% or thereabouts that would be ideal - and I know Editors/Reviewers are seeking more detail with less words, its tough, yet I sense you're up for the challenge - good luck).

The MS Addressed by R1 and R2 was 9,425 words (not counting Acknowledgments, References, Figure Captions, or Supplementary Material)

Every effort was made to reduce the length of the MS. The revised MS is now 9,280 words (not counting Acknowledgments, References, Figure Captions, or Supplementary Material); we only cut by 3% but added several new components suggested by R1, including more information on T-SSC relationships, a sensitivity analysis of T-SSC relationships, and Smearing estimate corrections for log-bias transformation in the storm metric-SSYEV relationships.

Cut by 15% would be 8,177 (not counting Acknowledgments, References, Figure Captions, or Supplementary Material)

3) Please respond to all comments using codes for each point. That is RXCY for reviewer comments where X is the reviewer number and Y is the reviewer comment number, for example R2C3 means Reviewer 2 Comment 3, AE1 is Associate Editor Comment 1, EC1 means Editor Comment 1. Using such codes will allow you to easily perform inter- and intra-reviewer crossing referencing which may allow your response letter to be more integrated, and also means that navigating through your response letter is easier. Provide your response directly after each comment and do not edit or shorten the comment. That is, even if the comment contains spelling errors do not correct them.

Do not change the order of the comments, the reviewers / editors have provided you with comments in a specific order, and expect your responses to be in the same order. If multiple comments are similar, so your response is similar, then please refer back to the detailed response, for example, "Please see our response to R1C3 for full details" as a response works.

In your response letter please make all of the following comments blue and your interleaved responses black. Where you wish to highlight line numbers in the revised MS please highlight with the yellow highlight option.

If the comment is editorial in nature (e.g., identifying a typographical error) then your response is a simple 'Done', obviously for comments of a scientific nature a more considered response will be required.

If you do not implement a reviewer's comment, then I expect that a well-reasoned scientific rebuttal is provided in your response letter. This is critically important.

Good luck making your revisions and substantially improving your manuscript; I look forward to seeing your revised manuscript and responses to the following comments when you're ready.
****

Dear Dr Messina
as you can see below, I have received two rather contrasting reviews! After reading the reviews, and re-reading your MS, I would suggest somewhere in the middle of the two reviews is about right. I do agree with R1 that there are some missing information on sampling protocols, and that it can be a little hard to

follow the logic of the analyses at times. R1 has done a very thorough job, and I would urge you too consider the comments around these issues carefully. There are a number of specific comments that you will need to consider also.

There are some questions around citations that you should think about. I might add that there has been some work done on how different road surfaces affect erosion rates (e.g., Sheridan and Noske, 2007, Hydrol. Procs, and others). I look forward to seeing your revision.

Patrick Lane
Associate Editor
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Reviewer #1:

R1C0:

Review Summary
I recommend this study for publication after major revision.

The manuscript (MS) presents a thorough case study of the effects of human disturbance on suspended sediment dynamics in a small, steep tropical watershed over event to interannual time scales. This study is of high technical merit. The work is justified by a lack of such characterizations of watersheds in this geophysical setting, as well as its applicability to sediment management in these regions, which is critical to coral reef management. Reporting effectively situated this work within the context of both the technical and applied canon in most cases.

However, there are many aspects of the reporting, from trivial to substantial, as well as several minor to moderate technical issues that will require a substantial amount of effort before this MS is ready for publication. These issues necessitate a recommendation for major revision. Major points of issue are detailed below, followed by line-specific comments.

It is my hope that the authors will take the thoroughness of this review as an encouragement, for only interesting pieces are worth such effort. I look forward to seeing a revised MS for review, and eventually in print.

R1C0 Response:
Thanks to the reviewer for a thorough and thoughtful review.

R1C1: Seven Substantial problems were identified with the reporting of methods and results. It is suggested that you:

1. Present effective overviews at the beginning of each section/subsection, including the development of a table or flowchart presenting your experimental overview.
Please try to remember that each section and sub-section are a unit of reporting. Each unit should begin with definitive statements providing an overview of the contents of the section/sub-section. At the manuscript scale I would suggest pulling together a table or flowchart presenting your experimental overview. This was briefly and generally presented at the end of the introduction, but the beginning of the methods section really demands a more technical break down of the experimental overview. At the section and sub-section scale I found that initial overviews were often incomplete, and in some cases followed by motivations, and then detailed accounts of each component, without ever introducing each component in the first place. It is important to give the reader the skeleton of what you are reporting at each turn, particularly when multi-step procedures, with multiple approaches as each step, have been employed.

R1C1 response:
Agreed--method overviews were added to the first paragraph of the Methods section, and all subsections, with substantial rewriting of the MS. A table or flowchart of methods would add to the length of the manuscript; we hope that the additional paragraphs are sufficient for clarity.

R1C2. Report on data at the beginning of the Methods section rather than the end.
On to sequencing: the reader needs to be informed about certain components of your work before others. In almost all work, one should report on data first or very early in the methods section. All analyses depend on the data, so the details of their collection and processing must come first to forestall unnecessary

uncertainty and questioning on the part of the reader.
[Editor: I agree here, this is what the proposed "Section 2 Study Site and Materials" refers to in my previous review.]

R1C2 response:
Agreed- the field data collection section has been moved to the beginning of the Methods section.
(we concluded that including all method information in the Study Site section would make the section too long).

Our internal reviewers previously commented that the data collection section belonged at the end of the Methods so that the development of the stage-Q and T-SSC relationships would not distract from the overall SSY modeling that is the main objective of the paper. They argued that the overall analytical approach should be described first so that it makes sense why each dataset was collected and how it is used to answer the research questions or accomplish the research objectives. I think this problem was mainly due to the uncertainty of how to treat the stage-Q and T-SSC components since each one has its own Methods, Results, and Discussion. Are they Methods with Results and Discussion that should be organized as such? Or were they just a component of Data Collection? We have now treated the stage-Q and T-SSC components as Data Collection (in Methods) since these are standard methods that have been used for many years and moved the technical details to the Appendices. Many papers simply don't include any of the technical details since they download the data from a website or the methods and results are detailed in a previous paper.

R1C2a. Furthermore, performing a flux based approach to investigating human impacts on natural processes, such as sediment production dynamics, is by necessity a series of stepwise procedures, which provides a basis for reporting structure. Of course the linearity of these operations (i.e. Step 2 dependent on the results of Step 1, etc.) can be complicated by recursive operations, whereby information gleaned from later steps can inform the reoperation of earlier steps. This phenomenon in concert with choices, such as the employment and comparison of multiple approaches to obtain the estimate at any given step, can complicate the process of crafting an effective methodological report. However, one must try to navigate an effective path through these complications to effectively communicate your program of research.

R1C2a response:
See R1C2 response. Yes, the question of treating the T-SSC relationship as simply a method to sample and calculate SSY or is it a preliminary result in and of its own. Since it is a widely applied method we have chosen to treat it as a sampling method to calculate SSY and treated it solely as Data Collection.

R1C3. Discussion elements incorporated in the Methods and Results sections.
You have elected to apply a Methods/Results/Discussion for the overall structure of the MS. However, Discussion material has been interdigitated with Methods and Results material. Reorganize as needed.

R1C3 response:
Done. Significantly reorganized the MS.

R1C4. Clear presentation of the relationship between sampling protocol and estimation of sub-watershed signals.
Sub-watersheds along a mainstem channel are nested, rather than discreet, i.e. the watershed of FG2 includes the watershed of FG1 rather than only the additional drainage area between FG1 and FG2 as implied in Fig.1 and in the text (p. 206-210). Make sure that you nail this point when introducing your study design/study region.

R1C4 response:
Done. The nested watersheds/subwatersheds are described in detail in 2^{nd} paragraph of Study Area and the calculation of SSY from each subwatershed is described in the Methods overview and Methods section 3.2.1

R1C5. Discuss all findings in the context of relevant literature.
The findings were very well discussed in the context of the canon of relevant literature, with the exception of section 5.1.

R1C5 response:
We added citations to relevant literature for section 5.1 where possible. Some Discussion findings are simply Discussion of observations ie interesting patterns in Q-SSC plots as a result of quarry operations (Section 5.1.1).

R1C6. Include the Appendix in your revision.
The Appendix was missing from the MS.R1. These materials contain a lot of information, some of which should be moved to the main body of the MS, and should certainly be included in the revision package. (I was able to access them from your first submission).

R1C6 response:
In EC9, the Editor requested the Appendices be submitted separately so the page count of the manuscript would be lower. In the interest of shortening the MS, as suggested by the Editor, the information in Appendices has been left there.

R1C7. Streamline sub-section headings.
On a minor note, I would suggest rewriting the sub-section heading by removing the 'Objective #' component - the continuity in the heading phrases is sufficient.
[Editor: good suggestion as it will provide a structure that is 100% clear.]

R1C7 response:
The subheadings have been revised and "Objective #" have been removed following R1C7 and the Editor comment agreeing with this change.

Technical

R1C8. Minor to moderate issues were found in some technical aspects of the work related to data/sample collection, accounting for log-bias, and error estimates. More information on the collection of some data/samples are needed, and a figure displaying the temporal distribution of monitoring/sampling efforts at each station would be a welcome addition.

R1C8 response:
We have clarified the sample collection method in the Methods overview. Please let us know if additional detail is necessary.

As for the temporal distribution of monitoring: Figure 3 shows when discharge was monitored at all stations and Tables 2 and 4 show when SSC was monitored and by which method. L216-218 also describe when monitoring was conducted. We opted against a separate figure showing sampling periods due to space constraints.

R1C8 cont. Log-linear (i.e. power law) relationships were used for some estimates of SSY and SSC, but the issue of log-bias was not investigated/corrected. See Duan (1983), Ferguson (1986), Gray et al. (2015), and others for guidance on this issue. I applaud the use of error estimates and the relatively transparent reporting of their computation. However, some important details are missing (see specific comments.)

R1C8 cont. response:
- SSC was predicted by a linear regression of T vs. SSC, so no log-bias correction was needed.
-Annual sediment yield was estimated by calculating the SSYEV for storms without measured Q and SSC using the SSYEV-Qmax model. Model performance metrics (r2 and RMSE) are in Table 6. We thought it would be too confusing or cluttered to add error estimates to the Annual SSY estimates since there are several different estimation methods, and their respective error estimation methods would be different.

Specific Comments (below these are mainly identified by line number)
R1C9. L8-11 Over what time period were the observations collected?

R1C9 response:
Done. Added "(2012-2014)" to text L10

R1C10. L16 Recommend stating that the human-disturbed watersheds 'have been estimated in increase loads'. For presumably that is what you did, rather than monitor the situation over the course of the initiation of human disturbance. If so, that should have been stated earlier.

R1C10 response:

Revised text: The human-disturbed subwatershed (5.2% disturbed) accounted for an average of 71-87% of SSY_{EV} from the watershed. Observed sediment load to the coast, including human disturbed subwatersheds, was 3.9x the natural background.

R1C11. L22 A yield is area normalized by standard definition. Here you are reporting loads (simply mass flux) and yields. Such detail is not needed in an abstract - just report the yields.

R1C11 response:
Done. Only reporting yields L22-23.

R1C12. L22 You defined SSYEV as event specific suspended sediment yield. How does one have an 'annual SSYEV'? Perhaps just 'annual SSY'?

R1C12 response:
Done. Changed to "SSY" L22-23.

R1C13. L26 Replace 'sediment yield increased significantly' with 'sediment yield from this area was 3.9X higher than undisturbed areas' or the like. Using terms like 'increased' in the abstract implies to many that you monitored the region over the period of change, which you did not.

R1C13 response:
This sentence was removed in rewriting the MS.

R1C14. L36 Recommend changing 'Sediment yield' to Suspended sediment yield' as this study did not address bedload.

R1C14 response:
Done.

R1C15. L45 Citation?

R1C15 response:
Revised MS text: "Anthropogenic sediment disturbance can be particularly high on volcanic islands in the humid tropics, where erosion potential is high due to high rainfall, extreme weather events, steep slopes, and erodible soils"

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

R1C16. L47 Citation?

R1C16 response:
Revised MS text: "Sediment yield in densely-vegetated watersheds can be particularly sensitive to land clearing, which alters the fraction of exposed soil more than in sparsely-vegetated regions."

Sentence removed.

R1C17. L48 Citation? i.e. Milliman & Syvitski 1992 or a more tropical specific pub?

R1C17 response:
Revised MS text:
"The steep topography and small floodplains on small volcanic islands further limits sediment storage and the buffering capacity of the watershed against increased hillslope sediment supply (Walling, 1999)"

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

R1C18. L79 Word choice: stating that an environment is 'challenging' does not inform one as to the 'challenges of…monitoring.'

R1C18 response:
Done. Removed "challenging"

Revised MS text:
"Knowledge of suspended sediment yield (SSY) under both natural and disturbed conditions on most tropical, volcanic islands remains limited, due to the challenges of in situ monitoring in these remote environments."

R1C19. L85 Define SSYEV here, as it is used in the body of the MS for the first time.

R1C19 response:
Removed "EV" since SSY is sufficient

R1C20. L85-88 Awkwardly worded sentence, revise.

R1C20 response:
Done.
Revised MS text:
"Models that predict SSY from small, mountainous catchments would establish baselines for change-detection, and improve regional-scale sediment yield models (Duvert et al., 2012)."

R1C21. L92 Citation for end of the sentence to illustrate 'interannual…relationship'. Recommend Gray et al. 2014 or the like.

R1C21 response:
Cited Gray et al. 2014 and added citation to Stock and Tribble 2010 for hysteresis in Hawaiian watersheds and Kostachuk 2002 for Fijian watershed.

R1C22. L104 Now only use the SSYEV acronym.

R1C22 response:
Done, except when presenting annual SSY.

R1C23. L133 Erosivity Index should be introduced before mention here.

R1C23 response:
The Erosivity Index was previously introduced with a reference in L105 (Kinnell 2013), and in the Abstract L22.

R1C24. L139 Section 2. Identify your study sub-watersheds in this section. I would suggest turning away from your FILE_BASED naming convention to something that isn't so jarring on the page.

R1C24 response:
Names were changed to lower case: Lower_Quarry instead of LOWER_QUARRY, and dentified sub-watersheds in the Study Area section, L139-L148, in the reference to Figure 1.

Now there are descriptions of the subwatersheds in Figure 1, in the second paragraph of Study Site, second paragraph of Methods section 3.2 L311-319, and in Table 1.

R1C25. L142 '(~3 km)' presumably stream length: label as such.

R1C25 response:
Done.

R1C26. L201 The opening paragraph of the Methods section should provide a more comprehensive overview. I realize that the Introduction ended with an overview of objectives and goals, but here the technical skeleton can be drawn.

R1C26 response:
Added MS text:
An additional paragraph was added to the Method section that introduce each of the subsequent sections:

The field methods used to calculate event-wise suspended sediment yield (SSY_{EV}) are described in section 3.1. The equations and analytical methods used to accomplish Objectives 1-3 are described in sections 3.12-

3.3, and 4. Briefly, the in-stream suspended sediment load (tons) and yield (SSY, tons/km^2) were calculated for individual storm events (SSY_{EV}) at three locations in Faga'alu watershed using calculated discharge (Q) and suspended sediment concentration (SSC)(Figure 1) during four field campaigns (Section 3.1). Each subwatershed had distinct land cover (forest at FG1, quarry and forest at FG2, and village and forest at FG3). Precipitation was recorded with a tipping bucket raingage (Section 3.1.1). Q was calculated from continuously recorded stage and a stage-discharge relationship calibrated with field measurements (Section 3.1.2). SSC was measured directly from grab samples or modeled from continuously monitored turbidity (T) and T-SSC relationships calibrated to in-stream SSC (Section 3.1.3). Storm events were identified using automated hydrograph separation, and SSY_{EV} calculated for each monitored location with Q and SSC data (Section 3.2.1). The subwatersheds were nested, so SSY_{EV} contributions from subwatersheds were calculated by subtracting SSY_{EV} at the upstream subwatershed from SSY_{EV} at the given downstream subwatershed. The sediment yield from disturbed surfaces was calculated assuming a uniform yield from forested parts of disturbed subwatersheds (Section 3.2.2). The cumulative probable error of SSY_{EV} was calculated for each storm to incorporate errors in Q and SSC (Section 3.2.3). Log-linear regression models were developed to predict SSY_{EV} from storm metrics for the undisturbed and disturbed subwatersheds (Section 3.3). Annual SSY was estimated from the regression models and the ratio of annual storm precipitation to the precipitation during storms where SSY_{EV} was measured (Section 3.4).

R1C27. L204-206 Start by informing us about your monitoring program. The three metrics listed here: Q, SSC, and SSY were not measured during the storms - you collected measurements and samples which were used to compute estimates later. What did you actually measure? This should be the leading section here, rather than cropping up after sections detailing the calculations of loads, yield and indices that rely on your monitoring data.

R1C27 response:
Descriptions of the data collection have been moved to the beginning of the Methods section.
See also responses to R1C2 and R1C2a

R1C28. L206-210 Here you introduce your watershed labels for the first time. This belongs in the previous section. More importantly, the wording of this section implies that you are sampling only the additional sub-watersheds at FG2 and FG3 rather than the integrated expression of all sub-watersheds upstream as all of your gage sites are situated along a mainstem drainage. This is an important distinction, as your analysis then relies on subtracting the loads calculated for upstream gage stations in order to arrive at estimates of sediment loads from given sub-watersheds. The entire study is designed around this concept, so it must be clearly communicated.

R1C28 response:
Done. Subwatersheds are defined in Study Area L139-147. SSY calculations are described in Section 3.2 L311-319. Here, in the overall description of Methods, we indicate L210-211 "SSYEV contributions from subwatersheds were calculated by subtracting the contribution of the upstream subwatershed."

R1C29. L221 What is 'quickflow?'

R1C29 response:
Hewlett and Hibbert (1967) proposed the term "quick flow" (also appears as "quickflow" in Dunne and Leopold (1978)) to describe the portion of the hydrograph caused by direct surface runoff during storms, to differentiate it from what they termed "delayed flow" or "baseflow", or the portion of the hydrograph that remains more or less constant during non-storm periods, fed by subsurface water. The EcoHydRology package in R separates the observed hydrograph into "quickflow" and "baseflow", we use the quickflow to define when storms occurred.

Revised text: Due to the large number of storm events and the prevalence of complex storm events observed at the study site, we used a digital filter signal processing technique (Nathan and McMahon, 1990) in the R-statistical package EcoHydRology (Fuka et al., 2014), which separates the hydrograph into quickflow, or direct surface or subsurface runoff that occurs during storms, and baseflow or delayed flow. Quickflow and baseflow components are not well defined in terms of hydrologic flowpath; here we use the separation operationally to define storm events.

R1C30. L221 You must mean 110% rather than 10%.

R1C30 response:

Done. Revised text:
"Spurious events were sometimes identified due to instrument noise, so only events with quickflow lasting at least one hour and peak quickflow greater than 10% of baseflow were included (See Appendix C for example)."

R1C31. L225 I am confused by your notation with the introduction of a new term 'specific sediment yield' (sSSY), which you identify as having units of mass/volume, while again identifying SSY as having units of volume. I suppose this is fine, as long as you are consistent (proof the MS diligently for this). But keep in mind that most literature identifies the mass flux of sediment as 'sediment load' or 'sediment discharge', while sediment yield usually denotes mass/area. I would suggest sticking with the more widely used convention.

R1C31 response:
The literature has varied definitions of yield and load. Our use of the terms SSY and sSSY is in line with Walling and Fang (2003) and Walling in other related publications who refer to "specific sediment yield" with units of tons/km2, and several others who also refer to "specific sediment yield" (e.g. Lenzi et al, 2003) as tons/km2. Milliman and Meade (1983) and Syvitski et al (2005) use yield as tons/km2 as suggested by the reviewer.

In L225 we define specific suspended sediment yield as "sSSY" with units of mass per area (tons/km2). We tried to keep from using "load" and "yield" so as not to confuse the reader, and use "specific yield" and define the units

R1C32. L230 Here you use the sediment load. Again, I would suggest sticking with convention (i.e. sediment load (mass), sediment yield (mass/area)).

R1C32 response:
See above response to R1C31.

R1C33. L230-244 Section 3.1.3: This section belongs in the discussion.

R1C33 response:
I agree that this section may be out of place here but I disagree that it belongs in Discussion. This section describes critical Methodological assumptions about our calculation of sediment yield and justifies our rationale for ignoring some components of the complete sediment budget like floodplain and in-channel deposition. If this was moved to Discussion, the reader may think our Methods are inappropriate or inadequate and be skeptical of our Methods and Results until much later in the Discussion section.
We moved this to the beginning of Methods section L197-207 so that we say up front that we're only calculating suspended yield and why. Hopefully the reader will then not be looking for how we calculated bedload. The MS then outlines the overall sampling and analytic methods before moving on to describing Field Data Collection.

R1C34. L231 Yes, an at-a-station fluvial suspended sediment budget, the counterpart to which is the fluvial bedload budget, which you should mention here as the component that was not measured.

R1C34 response:
Done. See response to R1C33.

R1C35. L247 (second to last sentence) Define 'Erosivity Index'.

R1C35 response:
Added MS text: "The Erosivity Index describes the erosive power of rainfall (Kinnell, 2013)."

R1C36. L247 (last sentence) Isn't SSYEV 'normalized by watershed area' sSSYEV by your notation system?

R1C36 response: Yes, that's correct. We kept the notation SSY to match with other literature, especially Duvert et al (2012), but wanted to explicitly point out to the reader that both SSY *and* the Q metrics are normalized by watershed area for the purpose of comparing the different sized watersheds.

R1C37. L254-273 Section 3.3: Please begin such sections with an overview of what was done in the first paragraph. In the first paragraph of this section you write broadly what was done, followed by motivation, followed by two of the approaches (Psum-SSYEV; Qmax-SSYEV), without ever introducing the third approach (SSYEV x PEVann/PEVmeas). Tell us upfront what your approaches were, and then report them in detail.

R1C37 response:
Done.
Added MS text:
"Annual SSY and sSSY were estimated using 1) the developed storm metric-SSY models, and 2) the ratio of annual storm precipitation to precipitation measured during storms with SSYEV data."

R1C38. L255 Style: That 'estimates' were 'estimated' is clear, without the clunky construction.

R1C38 response:
Done.

R1C39. L272-273 What does 'low' mean? Back up qualitative statements with quantitative examples.

R1C39 response:

Revised MS text:
"Equation 6 also ignores sediment yield during non-storm periods, which is justified by the low SSC (typically under 20 mg/L) and Q (baseflow) observed between storms."

R1C40. L274-287 Section 3.4: This should be the first paragraph of your methods section.

R1C40 response:
Done. The Methods section has been significantly reorganized. See our responses to R1C2 and R1C27

R1C41. L275-278 A figure illustrating the temporal distribution of sample/monitoring data collection by station would be appreciated.

R1C41 response:
It is difficult to visualize data from over 100 storms at three stations, or over the monitoring period given the various instrument errors at various locations. Instead we elected to show an example of one storm (Figure 4) to convey the general pattern of data collection and sediment dynamics during storms, and provide record of the temporal distribution of monitoring data in Figure 3, Tables 2 and 4. See our response to R1C8.

R1C42. L282-283 Report rain gage specifications (size, resolution).

R1C42 response:
Done, though the size certainly seems like a technical detail that could be looked up since we provided the make/model.

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

R1C43. L305-306 Assumed to be the same rather than just 'similar'. Is this a valid assumption? How do the major factors thought to contribute to specific water discharge differ between these sub-watersheds (average slope, vegetation)? A brief statement supporting this assumption would suffice.

R143 response:
Added MS text:
"The specific water discharge at FG2 is assumed to be the same as above FG1 since average slopes, vegetation, and soils of the watersheds are extremely similar."
We also describe the caveat that the quarry surface is continually disturbed and these are conservative estimates of SSY as a result.

R1C44. L320-322 Where was the ISCO's inlet positioned? Fixed or varied btw storms?

R1C44 response:
Inlet was fixed throughout the study.
Added MS text:
"The Autosampler inlet tubing was oriented down-stream, just below the water level sensor, approximately 30 cm above the stream bed, on rebar positioned midstream."

R1C45. L327-328 Why would you assume that SSC would ever be zero - particularly if you have enough baseflow samples over the course of your study to characterize this condition?

R1C45 response:
A similar approach was used in the literature (Lewis et al, 2001), and from field observations at the beginning of many storms it seemed like this was a good enough assumption based on the median SSC values during Non-Storm periods (varying from 5-60 mg/L at FG1-3). Even if SSC at the storm start was assumed to be higher it wouldn't make much of a difference in the total SSY calculation since it only spanned one or two intervals until a sample was collected, usually with far higher SSC in excess of several hundred mg/L.

R1C46. L341-343 The T-SSC relationship is too important to completely burry in your appendix. The basic details should be summarized here: model (i.e. linear, log-linear, etc.), were model assumptions met, etc.

R1C46 response:
Indeed, whole papers detailing the calibration of a T-SSC relationship for a single instrument and site are published (Minella et al., 2008). We felt that these methods are well-established at this point and we didn't have any novel contributions.

The T-SSC models were linear, added MS text: "A unique*, linear* T-SSC relationship…". We also added key assumptions:
The critical assumption in our application is that the parameters of the T-SSC relationship are stable over time and among storm events. The T-SSC relationship can be unique to each region, stream, instrument or even each storm event (Lewis et al., 2001), and can be influenced by water color, dissolved solids, organic matter, temperature, and particle shape, size, and composition.

Here the Methods section summarizes the r^2 values of the T-SSC relationships (which were high: 0.79-0.99), and RMSE % errors were added to Methods section. RMSE (mg/L) and % errors are also in Results section 4.2. Cumulative Probable Error. We thought this was a better place to describe the T-SSC relationship errors, showing the reader not only the error in the T-SSC relationships but how those errors propagate to the final SSY estimates to increase uncertainty. The reader is likely only interested in the details and errors of the T-SSC relationships for their impact on the final SSY calculations and the conclusions drawn from those calculations. Rather than simply provide the raw estimates of model error and leave the reader to infer how those errors impact the final calculations, we provide the error estimates in the context of the final SSY estimates.

A possible criticism could be that maybe SSY was higher at FG3 because of the steeper T-SSC relationship for the YSI at that location, compared to the YSI at FG1. We conducted a sensitivity analysis where we substituted the T-SSC relationship developed at FG1 for the steeper T-SSC relationship developed at FG3, to see how much the DR and % contributions would change. Using the same T-SSC relationship for both locations we found the DR decreased from 3.9 to 2.5, and the percent contributions changed from 13% Upper, 87% Total, to 20% Upper, 80% Total. We concluded these were relatively small changes to the overall story and maintained our overall conclusion that human disturbance has significantly increased sediment yields to coast.

If the reader requires more information on the T-SSC relationships, they are provided in the Appendix and we have added subplots zoomed in on the lower T-SSC values to increase confidence in the line-fitting. The intention was to not distract the reader from the main objectives or to lengthen the text with too much detail about the intermediary steps of the T-SSC relationship. The details of the T-SSC were provided in the Appendix because they are so critical, as R1 points out. We tried to strike a balance of placing the full technical detail in an Appendix while providing relevant information for addressing the research questions in the MS.

R1C47. L350 Equation 2: I applaud the transparent reporting of your method for sediment load uncertainty estimations. However, this equation appears to only relate to one approach to obtaining SSC (T-SSC rating curve), whereas your study employed a number of methods (linear interpolation of between SSC values, T-SSC rating, and assumed values for base flow). Also, if I understand your equation correctly, you don't need the summation symbol, as you indicate this operation with '+' signs.
Taking a step back, I would also suggest reconsidering your approach to error estimation.

R1C47 response:
We removed the summation symbol, and added error for interpolated grab samples to SSC measurement error.

Yes, the T-SSC model errors are included explicitly, the interpolated grab sample error was taken from the DUET-H/WQ look up table (5%) and included as measurement error for those SSYEV estimates. Only 3/42 storms used interpolated grab samples to calculate SSYEV.

As far as reconsidering the approach, there are definitely many different ways to estimate uncertainty so any suggestion of which method would be more appropriate are welcome. We chose this method since it was straightforward to calculate and well-documented in previous literature and a software tool (Harmel, Topping etc.).

R1C48. L356-359 Why not calculate the uncertainty associated with this estimate? It is after all just another estimate, merely arrived at by arithmetic processing of two other estimates…

R1C48 response:
Yes it could be simple arithmetic to take the mean of the UPPER and TOTAL error estimates, or following the cumulative probable error method it would be necessary to calculate PE based on all measurement and model errors at FG1 and FG3, thereby increasing the uncertainty in FG2 even more. There was no clear evidence that either was the appropriate method and it would significantly complicate the error estimation to include another section in the MS on comparing error estimates from different methods.

R1C49. L365 No difference at all? Would be nice to see those data, at least in an appendix.

R1C49 response:
Revised MS text:
"Linear relationships between daily P at RG1 and Wx (slope=0.95, r2=0.87) and RG1 and RG2 (slope=0.75, r2=0.85) were observed. Higher P was expected at higher elevation at RG2 so lower P at RG2 was assumed to be caused by measurement error, as the only available sampling location was a clearing with high surrounding canopy."

R1C50. L419-427 Discussion material. Some interpretation of results certainly belongs in the Results section, but there is a line, and this appears to be over it.

R1C50 response:
Done.
Moved to Discussion section 5.1.1 Compare SSC for disturbed and undisturbed watersheds in Faga'alu

R1C51. L476 It appears that you have chosen your SSC grab sample error from a table. Do you think this is a realistic error in terms of the depth-concentration profile expected for the flow fields and particle size distribution characteristics that you encountered?

R1C51 response:
Without any data to estimate this, I can only assume this is a realistic error estimate. The study site stream is extremely well mixed given the high slope and energetic flow. Our motivation was mainly to quantify sediment yields to coral reef areas, and so our focus was particles that would stay in suspension in fairly calm water, long enough to be transported from the stream mouth to corals. Hence, we did not do any depth-integrated sampling.

R1C52. L485-486 How did you arrive at 5% error associated with interpolation between SSC samples? Also, you have estimated your grab sample error as 3% - do you think this is a realistic error in terms of representation of the average SSC in consideration of the depth-concentration profile expected for the flow fields and particle size distribution characteristics that you encountered?

R1C52 response:
The 5% error was taken from the DUET-H/WQ lookup table, default value (values can range from 0-21%) (Harmel et al., 2009). Considering SSC values of grab samples regularly exceeded 1,000 mg/L we're considering 3% errors of 30 mg/L or more. See our response to R1C52.

R1C53. L486-487 Was sample analysis error estimated from replicates, on the basis of known compounded measurement precision, or simply assumed?

R1C53 response:
Errors were taken from DUET-H/WQ software Lookup Tables, using default values, unless they were from the models provided in the Appendices. We did not do replicate sample analysis.

R1C54. L487-489 Did your SSC-turbidity models meet the basic assumptions for attributing a single error estimate to dependent variable estimates produced over the entire independent variable domain (i.e homoscedastic and normally distributed residuals)? Also, as these models are buried in an appendix, the reader has no knowledge at this point as to their basic formulation (log-linear? Basic assumptions for regression met?). See Helsel and Hirsch (2002) for guidance on regression assumptions and error estimates from regression. As the MS is long, it makes sense to shunt methodological details to an appendix, but such fundamental details should still be reported in the main text.

R1C54 response:
See our response to R1C46.

R1C55. Table 2. Ditch the 'Upper' and 'Lower' and just report the gage codes, as that is what one can reference off of the study location map.

R1C55 response:
We also struggled with how to refer to the subwatershed areas versus the sampling locations. As pointed out in R1C28 all gages on the mainstem channel receive flow from upstream subwatersheds. If referred to as gage codes FG1, FG2, FG3 these would imply the SSY measured at these gages. The terms LOWER, LOWER_QUARRY, etc. mean these SSY values in Table 2-5 are calculated as the difference of the measurements at the gages to isolate the runoff from particular subwatersheds by subtracting runoff from upstream subwatersheds. These watershed labels are referenced on the study location map just as the gages are (Fig. 1). These labels are also intended to quickly convey which sediment sources are being referenced, ie Upper means natural forest, Lower_Quarry means from the quarry in the Lower, human-disturbed watershed etc.

R1C56. L492-493 Reference the relevant figure/table.

R1C56 response:
Done.

R1C57. L519-520 Reiterate what you are comparing here (between stations) for the sake of clarity - this is a long MS with multiple components and many readers would have to flip back to the methods here to refresh. Also, reference the relevant table/figure.

R1C57 response:
Done.

R1C58. L565-580 Incorporate previous studies into your discussion (as you have done in 5.2).

R1C58 response:
Done. See our response to R1C5.

R1C59. L597-599 Note that with Asselman (2000) you are referring to Q-SSC relationships rather than Qmax-SSY.

R159 response:
Yes, Asselman (2000) was just a good reference for interpreting slope values in the Q-SSC relationship, but we feel it would extend to Qmax-SSY as well.

R1C 60. L628-639 Nice follow-up with Milliman and Syvitski (1992) relationship. Also note the size of your headwater drainage area relative to their study areas, and how sediment yield generally scales with drainage area, which would further support your findings. Also note the short duration of your study.

R160:
Done.
Added MS text:
"Faga'alu is also a much smaller watershed and the study period was relatively short (3 years) compared to others included in their models."

R1C61. L640-665 Note the monitoring base period for these studies in comparison to each other and yours.

R1C61 response:
Done. To shorten the MS in response to Editor and R1 request, this section was significantly cut down.
Revised MS text:
"Sediment yield was measured from two Hawaiian watersheds which are physiographically similar though much larger than Faga'alu: Hanalei watershed on Kauai ("Hanalei", 54 km²), and Kawela watershed on Molokai ("Kawela", 14 km²) (Table 8) (Ferrier et al., 2013; Stock and Tribble, 2010). Hanalei had slightly higher rainfall (3,866 mm/yr) than Faga'alu (3,247 mm/yr) but slightly lower SSC (mean 63 mg/L, maximum of 2,750 mg/L) than the Total Faga'alu watershed (mean 148 mg/L, maximum 3,500 mg/L) (Ferrier et al., 2013; Stock and Tribble, 2010). Kawela is drier than Faga'alu (P varies with elevation from 500-3,000 mm) and had much higher SSC (mean 3,490 mg/L, maximum 54,000 mg/L) than the Total Faga'alu watershed. SSY from Hanalei was 369 ± 114 tons/km2/yr (Ferrier et al., 2013), which is higher than the undisturbed subwatershed in Faga'alu (45-68 tons/km2/yr) but similar to the disturbed (430-441 tons/km2/yr) subwatersheds. Stock and Tribble (2010) estimated SSY from Kawela was 459 tons/km²/yr, similar to the disturbed Lower Faga'alu watershed, but nearly twice as high as the Total Faga'alu watershed. Overall, both Hawaiian watersheds have higher SSY than Faga'alu, which is consistent with the low Qmax-SSYEV intercepts and suggests Faga'alu has relatively low erosion rates for a steep, volcanic watershed. Precipitation variability may contribute to the difference in SSY, so a more thorough comparison between Hanalei and Faga'alu would require a storm-wise analysis of the type performed here."

R1C62. Appendix 4 As the T-SSC relationships are a fundamental pillar of your SSY estimations, they need to be detailed here in terms of model formulations, model assumptions, and statistical descriptors of fit. More realistic assessments of total model (SSY) error is contingent upon the error associated with these estimates.

R1C62 response:
Statistical descriptors of fit: we provide r^2, RMSE and % error, similar to Minella et al. (2008) who wrote a whole paper on the calibration of a single T-SSC relationship.

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Reviewer #2:

R2C0. Generally this paper is now in very good shape and I recommend it for publication more or less as it stands. I note that it has already gone through the review process so it seems well polished. I am notoriously bad at picking up typos and only picked up a couple of problems.

R2C0 response: Thank you, we appreciate the positive review.

R2C1. The conversion factor in equation 1 from mg to tons which should be 10^-9 .
R2C1 response:
Done. Good catch.

R2C2. The units drawn on figure A2.2 need to use superscripts for square (2) and cubic (3) meters
R2C2 response:
Done.

R2C3. In line with modern trends I think the Introduction section and Discussion section are both too long. In my view the results stand by themselves and need little elucidation. But this is probably more a reflection of my age and mathematical bent where equations are my friend and words are not, than a problem with the paper. I'll leave that one to the editor.
R2C3 response:
We cut the MS down by 3%.

R2C4. I was particularly happy that there was lots of data used in this paper and there was a decent error analysis. To show just how pedantic a reviewer can be, I object to the three significant figure accuracy claimed for the RMSE used in line 484 (16.3%). Perhaps leave this at 16% and similarly in line 479 (8.5 to 8%).
R2C4 response:
Done.

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TITLE:

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

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ABSTRACT

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Suspended sediment concentrations (SSC) and yields (SSY) ~~were measured~~ during storm and non-storm periods, 2012-2014, were measured from undisturbed and human-disturbed portions of a small (1.8 km²), mountainous watershed that drains to a sediment-stressed coral reef. Event-wise SSY (SSY_{EV}) was calculated for 142 storms from measurements of water discharge (Q), turbidity (T), and SSC measured downstream of three key sediment sources: undisturbed forest, an aggregate quarry, and a village. SSC and SSY_{EV} were significantly higher downstream of the quarry during both storm- and non-storm periods. The human-disturbed subwatershed (10.1% disturbed) accounted for an average of ~~71~~ 87% of SSY_{EV} from the ~~total~~ watershed~~, and has increased loads~~. Observed sediment yield (mass) to the coast~~ by~~, including human disturbed subwatersheds, was 3.9x ~~over~~the natural background. Specific SSY (~~tons~~mass/area) from the disturbed quarry area was 49x higher than from natural forest compared with 8x higher from the village~~. The quarry, which covers 1.1% of the total watershed area, contributed 36% of total SSY_{EV} at the outlet.~~ area. Similar to mountainous watersheds in semi-arid and temperate climates, SSY_{EV} from both the undisturbed and disturbed watersheds correlated closely with

maximum event discharge (Qmax), event total precipitation and event total Q, but not with ~~a precipitation erosivity index.~~the Erosivity Index. Best estimates of annual ~~SSY_{EV}~~SSY varied by method, from ~~41-61 tons/yr (~~45-~~68~~143 tons/km^2/yr~~)~~ from the undisturbed subwatershed, ~~310-388 tons/yr (350-~~441-598 tons/km^2/yr~~)~~ from the human-disturbed subwatershed, and ~~360-439 tons/yr (200-247~~241-368 tons/km^2/yr~~)~~ from the total watershed. Sediment yield was very sensitive to disturbance; ~~only 5.2~~the quarry covers 1.1% of the total watershed ~~is disturbed by humans~~area, but contributed 36% of SSY_{EV}. Given the limited access to gravel for infrastructure development, sediment ~~yield increased significantly (3.9x). While unpaved roads are often identified as a source of sediment in humid forested regions, field observations suggested that most roads in the urban area were paved or stabilized with aggregate. Repeated surface~~ disturbance ~~at the quarry is a key process maintaining high rates of sediment generation. Given the large distance to other sources of building material,~~from local aggregate mining ~~and associated sediment disturbance~~ may be a critical sediment source on remote islands in the Pacific and elsewhere. Identification of ~~sediment~~erosion hotspots like the quarry using rapid, event-wise measures of suspended sediment yield will help efforts to mitigate sediment ~~loads~~stress and restore coral reefs.

Keywords:

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

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1. Introduction

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Human ~~activities~~disturbances including deforestation, agriculture, ~~road construction~~roads, mining, and urbanization alter the timing, composition, and amount of sediment loads to downstream ecosystems (Syvitski et al., 2005). Increased sediment ~~loads~~yields can stress aquatic ecosystems downstream of impacted watersheds, including coral reefs~~ that occur near the outlets of impacted watersheds. Sediment impacts coral~~, by decreasing light for photosynthesis and increasing sediment accumulation rates (Fabricius, 2005; Storlazzi et al., 2015). ~~Anthropogenic sediment disturbance can be particularly high on volcanic islands in the humid tropics, which have a high potential for erosion due to high rainfall, extreme weather events, steep slopes, and erodible soils. Sediment yield in densely vegetated watersheds can be particularly sensitive to land clearing, which alters the fraction of exposed soil more than in sparsely-vegetated regions. The steep topography and small floodplains on small volcanic islands further limits sediment storage and the capacity of the watershed to buffer increased hillslope sediment supply. Such environments characterize many volcanic islands in the south Pacific where coral reefs are impacted by sediment.~~Anthropogenic sediment disturbance can be particularly high on volcanic islands in the humid tropics, where erosion potential is high due to high rainfall and steep slopes (Milliman and Syvitski, 1992). The steep topography and small floodplains on small volcanic islands limits sediment storage and the buffering capacity of the watershed against increased hillslope sediment supply (Walling, 1999). Such environments characterize many volcanic islands in the South Pacific and elsewhere where many coral reefs are sediment-stressed (Bégin et al., 2014; Fallon et al., 2002; Hettler et al., 1997; Rotmann and Thomas, 2012).

~~A large proportion of a watershed's sediment yield can originate from disturbed areas that cover a relatively small fraction of the watershed area. Unpaved roads covering 0.3-0.9% of the watershed area were the dominant sediment source in disturbed watersheds on St. John in the Caribbean, and increased sediment yield to the coast by 5-9 times~~A large proportion of sediment yield can originate from disturbances that cover small fractions of the watershed area, suggesting management should focus on erosion hotspots. In the grazing-disturbed Kawela watershed on Molokai, Hawaii, most of the sediment originated from less than 5% of the watershed area, and 50% of the sediment originated from only 1% of the watershed (Risk, 2014; Stock et al., 2010). On St. John in the Caribbean, unpaved roads covering 0.3-0.9% of the watershed were the dominant sediment source, and increased sediment yield to the coast by 5-9x relative to undisturbed watersheds (Ramos-Scharrón and Macdonald, 2007). In the U.S. Pacific Northwest ~~of the United States, several studies found,~~ most road-generated sediment ~~can originate~~originated from just a small fraction of unpaved roads (Gomi et al., 2005; Henderson and Toews, 2001; Megahan et al., 2001; Wemple et al., 1996), and heavily used roads ~~could generate 130 times~~yielded 130x as much sediment as abandoned roads (Reid and Dunne, 1984). ~~In a watershed disturbed by grazing on Molokai, Hawaii, less than 5% of the land produces most of the sediment, and only 1% produces approximately 50% of the sediment (Risk, 2014; Stock et al., 2010), suggesting that management should focus on identifying, quantifying, and mediating erosion hotspots.~~

Sediment management requires linking changes in land use~~ changes and mitigation strategies~~ to changes in sediment yields at the watershed outlet (Walling and Collins, 2008). A sediment budget quantifies sediment ~~as it moves~~movement from key sources like hillslope erosion, channel-bank erosion, and mass movements, to its eventual exit from a watershed (Rapp, 1960). Walling (1999) used a sediment budget to show that sediment yield from watersheds can be insensitive to ~~both~~ land use change and erosion management due to high sediment storage capacity on hillslopes and in the channel. Sediment yield from disturbed areas can also be large but ~~may not be important~~relatively unimportant compared to ~~naturally~~ high yields from undisturbed areas. ~~While a full description of all sediment production and transport processes are of scientific interest, the~~ The sediment budget ~~needs to~~can be simplified ~~to be used as a management tool~~since most applications require only the order of magnitude or relative importance of processes be known (Slaymaker, 2003). ~~Most management applications require only that the order of magnitude or the relative importance of process rates be known, so~~ Reid and Dunne (1996) argue a management-focused sediment budget can be developed quickly ~~in situations~~ where the ~~management~~ problem is clearly defined and the management area can be divided into homogenous sub-units.

Knowledge of suspended sediment yield (SSY) under both natural and disturbed conditions on most tropical, volcanic islands remains limited, due to the challenges of in situ monitoring in ~~these~~ remote~~, challenging~~ environments. ~~The limited data has also made it difficult to develop reliable sediment yield models for ungauged watersheds.~~ Existing ~~sediment yield~~erosion models are ~~often~~mainly designed for agricultural landscapes~~ and~~, which are not well-calibrated to the ~~climatic, topographic, and geologic conditions found on~~ physical geography of steep, tropical islands~~. Most readily available models also do not incorporate many of the~~, and ignore important processes ~~that generate sediment in steep watersheds, including~~like mass movements (Calhoun and Fletcher, 1999; Ramos-Scharrón and Macdonald, 2005; Sadeghi et al., 2007). ~~Developing models~~Models that predict ~~SSY_{EV}~~SSY from small, mountainous catchments ~~is a significant contribution for establishing~~would establish baselines for change-detection ~~for sediment mitigation projects~~, and ~~can also further~~ improve ~~models applied at the~~ regional~~-~~scale sediment yield models (Duvert et al., 2012).

Traditional approaches to quantifying human impact on sediment budgets~~, including~~ include comparison of total annual yields (Fahey et al., 2003) and sediment rating curves

(Asselman, 2000; Walling, 1977)~~, are complicated by interannual climatic variability and hysteresis in the discharge-concentration relationship.~~. These approaches are complicated by interannual climatic variability and hysteresis in the discharge-sediment concentration relationship (Ferguson et al., 1991; Gray et al., 2014; Kostaschuk et al., 2002; Stock and Tribble, 2010). Sediment yield can be highly variable over various time scales, even under natural conditions. At geologic time scales, ~~if an undisturbed~~sediment yield from a disturbed watershed ~~is not in a steady-state condition, sediment yields~~ may decrease ~~over time~~ as it reaches ~~equilibrium~~steady-state, or ~~the~~ sediment contributions from ~~different~~ subwatersheds may change with time (Ferrier et al., 2013; Perroy et al., 2012). At decadal scales, cyclical climatic ~~variability~~patterns like El Nino-Southern Oscillation ~~(ENSO)~~ events or Pacific Decadal Oscillation ~~(PDO) patterns~~ can significantly alter sediment yield from undisturbed watersheds (Wulf et al., 2012).

~~As an alternative to comparing annual sediment loads,~~ SSY generated by storm events of the same magnitude can be ~~compared~~used to ~~assess~~compare the contribution of ~~individual~~ subwatersheds to total SSY (Zimmermann et al., 2012), determine temporal changes in SSY ~~from the same watershed over time~~ (Bonta, 2000), and ~~compare the responses of different watersheds~~relate SSY to various precipitation or discharge variables ("storm metrics") (Basher et al., 2011; Duvert et al., 2012; Fahey et al., 2003; Hicks, 1990). The relative anthropogenic impact on SSY_{EV} may vary by storm magnitude, as documented in Pacific Northwest forests (Lewis et al., 2001). As storm magnitude increases, water yield and/or SSY_{EV} from natural areas may increase relative to human-disturbed areas, diminishing anthropogenic impact relative to the natural baseline. While large storms account for most SSY under undisturbed conditions, the disturbance ratio (DR) may be highest for small storms, when background SSY_{EV} from the undisturbed forest is low and erodible sediment from disturbed surfaces is the dominant source (Lewis et al., 2001). For large storms, mass movements and bank erosion in undisturbed areas can increase the natural background and reduce the DR for large events.

Event-wise SSY (SSY$_{EV}$) may correlate with storm metrics such as total precipitation, the Erosivity Index (EI) (Kinnell, 2013), or total discharge, but the best correlation has consistently been found with maximum event discharge (Qmax). The EI quantifies the erosive energy of rainfall. Several researchers have hypothesized that Qmax integrates the hydrological response of a watershed, making it a good predictor of SSY$_{EV}$ in diverse environments (Duvert et al., 2012; Rankl, 2004). High correlation between SSY$_{EV}$ and Qmax has been found in semi-arid, temperate, and sub-humid watersheds in Wyoming (Rankl, 2004), Mexico, Italy, France (Duvert et al., 2012), and New Zealand (Basher et al., 2011; Hicks, 1990), but this approach has not been attempted for steep, tropical watersheds on volcanic islands.

~~The anthropogenic impact on SSY$_{EV}$ may vary by storm magnitude, as documented in Pacific Northwest forests (Lewis et al., 2001). As storm magnitude increases, water yield and/or SSY$_{EV}$ from natural areas may increase relative to human-disturbed areas, diminishing anthropogenic impact relative to the natural baseline. While large storms account for most SSY under undisturbed conditions, human-disturbed areas may show the largest disturbance, expressed as a percentage increase above the natural background, for smaller storms (Lewis et al., 2001). The disturbance ratio (DR) may be highest for small storms, when background SSY$_{EV}$ from the undisturbed forest is low and erodible sediment from disturbed surfaces is the dominant source. For large storms, mass movements and bank erosion may contribute to naturally high SSY$_{EV}$ from undisturbed watersheds, increasing the background and reducing the DR for large events.~~

This study uses in situ measurements of precipitation (P), ~~stream~~water discharge (Q), turbidity (T) and suspended sediment concentration (SSC) to accomplish three objectives~~:~~ ~~Objective 1)~~ and answer the following research questions:

1) Quantify suspended sediment concentrations (SSC) and yields (SSY) ~~from~~at the outlets of undisturbed and human-disturbed portions of ~~a small~~Faga'alu watershed ~~in the south Pacific~~ during storm and non-storm periods. ~~The research questions addressed under this objective include:~~ How does SSC vary between storm and non-storm periods? How much has human disturbance increased ~~suspended sediment yield to the coast~~SSY during storm events? ~~What human activities~~Which land uses dominate the anthropogenic contribution to ~~suspended sediment yield? How do concentrations vary between storm and non-storm periods? Objective 2)~~ SSY?
2) Develop an empirical model ~~of SSY during storm events (SSY_{EV}). This objective will answer the questions:~~to predict SSY_{EV} from easily-monitored discharge or precipitation metrics. Which storm metric is the best predictor of SSY_{EV}~~: total event precipitation, Erosivity Index, total event discharge, or maximum event discharge? How do sediment contributions from undisturbed areas and human-disturbed areas~~? How does human-disturbance to SSY vary with storm ~~size? Objective 3)~~ metric?
3) Estimate annual ~~sediment yields~~SSY using the measurements from Objective 1, and modeling results from Objective 2. How does SSY at the field site compare ~~with~~to other volcanic tropical islands~~. This objective will use the results from Objective 2 to model annual sediment load from the study watersheds, for comparison with other literature on volcanic tropical islands and disturbed watersheds.~~ and other disturbed watersheds?

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2. Study Area

~~The study~~Faga'alu (Fong-uh ah-loo) watershed~~, Faga'alu,~~ is located on Tutuila (14S, 170W), American Samoa~~. Tutuila has~~, which is comprised of steep, heavily forested mountains with villages and roads mostly confined to the flat, coastal areas~~ near the coast. The main stream in Faga'alu (~3 km) drains an area of 1.78 km² into Faga'alu Bay (area draining to FG3 in Figure 1). The mean slope of the main Faga'alu watershed is 0.53 m/m and total relief is 653 m. The administrative boundary of Faga'alu includes the watersheds of the main stream and several small ephemeral streams that drain directly to the bay (0.63 km²) (grey dotted boundary in Figure 1).~~. The coral reef in Faga'alu Bay is highly degraded by sediment (Fenner et al., 2008)~~,~~ and Faga'alu watershed was selected by the US Coral Reef Task Force (USCRTF) as a Priority Watershed for conservation and remediation efforts (Holst-Rice et al., 2015).

The administrative boundary of Faga'alu includes the watersheds of the main stream (1.78 km²) and several small ephemeral streams that drain directly to the bay (0.63 km²) (grey dotted boundary in Figure 1, "Admin."). Faga'alu watershed is drained by the main stream, which runs ~3 km from Matafao Mountain to Faga'alu Bay (area draining to FG3 in Figure 1, "Total" watershed). The Total watershed can be divided into an undisturbed, Upper watershed (area draining to FG1, "Upper"), and a human-disturbed, Lower watershed (area draining to FG3, "Lower"). The Lower watershed can be further subdivided to isolate the impacts of an aggregate quarry (area draining between FG1 and FG2, "Lower_Quarry") and urbanized village area (area draining between FG2 and FG3, "Lower_Village") (Figure 1).

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Faga'alu occurs on intracaldera Pago Volcanics formed about 1.20 Mya (McDougall, 1985). Soil types in the steep uplands are rock outcrops (15~~%) with~~% of the watershed area) and well-drained Lithic Hapludolls ranging from silty clay to clay loams 20-150 cm deep (Nakamura, 1984). Soils in the lowlands include a mix of deep (>150 cm), well drained very stony silty clay loams, and poorly drained silty clay to fine sandy loam along ~~streams and~~ valley bottoms. The mean slope of Faga'alu watershed is 0.53 m/m and total relief is 653 m.

2.1 Climate

Annual precipitation (P) in Faga'alu watershed is 6,350 mm at Matafao Mtn. (653 m m.a.s.l), 5,280 mm at Matafao Reservoir (249 m m.a.s.l.) and ~~about~~ ~3,800 mm on the coastal plain (Craig, 2009; Dames & Moore, 1981; Perreault, 2010; Tonkin & Taylor International Ltd., 1989; Wong, 1996). There are two ~~subtle~~ rainfall seasons: a drier winter ~~season~~ from June through September ~~that~~ accounts for 25% of annual ~~precipitation~~P, and a wetter summer ~~season,~~ from October through May accounts for 75% of annual P ~~(Perreault, 2010; data from USGS rain gauges and Parameter-elevation Relationships on Independent Slopes Model (PRISM) Climate Group (Daly et al., 2008)). While total rainfall is lower in the drier season, large storm events are still observed. At 11 sites around the island, 35% of annual peak flows occurred during the drier season over 1959-1990~~(Craig, 2009; Perreault, 2010). P is lower in the drier season but large storms still occur: at 11 stream gages around the island, 35% of annual peak flows occurred during the drier season (1959-1990) (Wong, 1996).

2.2 Land Cover and Land Use

2.2.1~~.~~ Vegetation, agriculture, and urban areas

The predominant land cover in Faga'alu watershed is undisturbed vegetation ~~(94.8~~on the steep hillsides (95%), including forest (~~85.7~~86%) and scrub/shrub (9~~.0%) on the steep hillsides~~

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~~(~~(%) (Table 1). The ~~upper~~Upper watershed~~, draining to FG1 in Figure 1,~~ is dominated by undisturbed rainforest (82%) on steep hillslopes~~.~~ ~~with no human disturbance.~~ The ~~lower~~Lower subwatershed~~, draining areas between FG1 and FG3 in Figure 1,~~ has steep, vegetated hillslopes and a relatively small flat area in the valley bottom that is urbanized (~~3.2% of the watershed area~~6.4% "High Intensity Developed" in Table 1). A small portion of the watershed (~~0.9~~1.8%) is developed open space, ~~which includes~~mainly landscaped lawns and parks. ~~In addition to some~~Agricultural areas include small household gardens ~~there are several~~ and small ~~agricultural~~ areas of banana and taro on the steep hillsides~~. These agricultural plots were~~, classified as grassland (0.~~2~~3% GA, Table 1) due to ~~the~~ high fractional grass cover ~~in the plots. There are several small footpaths and unpaved driveways in the village, but most~~. Most unpaved roads are stabilized with compacted gravel and do not appear to be a major ~~contributor of~~ sediment source (Horsley-Witten, 2012).

<Table 1 here please>

2.2.2 Aggregate quarry and reservoirs

An ~~open-pit~~ aggregate quarry ~~covers~~covering 1.6 ha ~~and accounts for nearly all of the bare land (1.1% of the watershed) (Table 1). The quarry~~ has been in continuous operation since the 1960's (Latinis et al., 1996)~~. With few sediment runoff controls~~ and accounted for nearly all of the bare land in ~~place, sediment has been~~Faga'alu watershed (1.1%) (Table 1). Sediment eroded from the quarry was discharged directly to Faga'alu stream~~. In~~ until 2011, ~~the~~when quarry operators installed ~~some sediment runoff management practices such as~~ silt fences and small settling ponds (Horsley-Witten, 2011) ~~but they~~, which were ~~unmaintained and~~ inadequate to control the large amount of sediment mobilized during ~~storm events~~storms (Horsley-Witten, 2012). During the study period (2012-2014), additional sediment ~~control measures~~controls were

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installed and ~~some~~ large piles of overburden were overgrown by vegetation (Figure 2~~), altering the sediment availability.~~). In late 2014, after the monitoring reported here, large ~~sediment~~ retention ponds were installed to ~~mitigate~~capture sediment runoff~~, but these mitigation activities happened after the sample collection reported here~~. See Holst-Rice et al. (2015) for ~~a full~~ description of sediment mitigation ~~efforts~~ at the quarry.

<Figure 2 here please>

Three water impoundment structures were built in the early ~~20th century~~1900's in the ~~upper part of the~~Upper watershed for drinking water supply and hydropower, but none are in use and the ~~one~~reservoir at FG1 is filled with ~~sediment. We~~coarse sediment. Other deep pools at the base of waterfalls in the upper watershed have no fine sediment and we assume the other reservoirs are ~~similarly filled with coarse sediment and are~~ not ~~currently~~ retaining fine suspended sediment. A full description of ~~stream impoundments~~the reservoirs is in ~~Appendix~~Supplementary Material A.

3. Methods

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The field methods used to calculate event-wise suspended sediment yield (SSY_{EV}) are described in section 3.1. The equations and analytical methods used to accomplish Objectives 1-3 are described in sections 3.2-3.4. Briefly, the in-stream suspended sediment yield (SSY, tons) and specific suspended sediment yield (sSSY, tons/km^2) (*sensu* Walling and Webb (1996)) were calculated for individual storm events (SSY_{EV}, $sSSY_{EV}$) at three locations in Faga'alu watershed using calculated discharge (Q) and suspended sediment concentration (SSC)(Figure 1) (Section 3.1). Q was calculated from continuously recorded stage and a stage-discharge relationship calibrated with field measurements (Section 3.1.2). SSC was measured directly from grab samples or modeled from continuously monitored turbidity (T) and T-SSC relationships calibrated to in-stream SSC (Section 3.1.3). Storm events were identified using automated hydrograph separation, and SSY_{EV} calculated for each monitored location with the Q and SSC data (Section 3.2.1). The subwatersheds were nested, so SSY_{EV} contributions from subwatersheds were calculated by subtracting SSY_{EV} at the upstream subwatershed from SSY_{EV} at the given downstream subwatershed. SSY from disturbed surfaces was calculated assuming a spatially uniform SSY from forested parts of disturbed subwatersheds (Section 3.2.2). The cumulative probable error (PE) of SSY_{EV} was calculated for each storm to incorporate errors in Q and SSC, and different T-SSC relationships were tested for their impact on SSY estimates (Section 3.2.3). Log-linear regression models were developed to predict SSY_{EV} from storm metrics for the undisturbed and disturbed subwatersheds (Section 3.3). Annual SSY was estimated from the regression models and the ratio of annual storm precipitation to the precipitation during storms where SSY_{EV} was measured (Section 3.4).

Measurements of SSY at FG1, FG2 and FG3 quantify the in-stream suspended sediment budget. Other components of sediment budgets not measured in this study include channel erosion, channel deposition, and floodplain deposition (Walling and Collins, 2008). In Faga'alu, the channel bed is predominantly large volcanic cobbles and gravel, with no significant deposits of fine sediment. Upstream of the village, the valley is very narrow with no floodplain. In the Lower watershed the channel has been stabilized with cobble reinforced by fencing, so overbank flows and sediment deposition on the floodplain are not observed. We therefore assume that channel erosion and channel and floodplain deposition are insignificant components of the sediment budget, and the measured sediment yields at the three locations reflect differences in hillslope sediment supply.

3.1 Field Data Collection

Data on P, Q, SSC, and T were collected during four field campaigns: January-March 2012, February-July 2013, January-March 2014, and October-December 2014, and several intervening periods of unattended monitoring by instruments with data loggers. Field sampling campaigns were scheduled to coincide with the period of most frequent storms in the November-May wet season, though large storms were sampled throughout the year.

~~The equations used to accomplish Objectives~~ 3.1~~-3 are described~~.1 Precipitation (P)

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P was measured in ~~sections 3.1-3.3,~~Faga'alu watershed from January, 2012, to December, 2014, using a tipping-bucket rain gage located at the quarry near the centroid of the watershed (RG1; 20cm dia., 1-minute resolution) and ~~the field methods~~a Vantage Pro Weather Station located at the stream outlet to ~~measure~~the ocean (Wx; 20cm dia. 15-minute resolution) (Figure 1). Data from a third rain gage, (RG2) was recorded from January to March, 2012 to determine an orographic precipitation relationship. Total event precipitation (Psum) was calculated using 1 min interval data from RG1, with data gaps filled by 15-minute interval precipitation data from Wx.

3.1.2 Water Discharge (Q)

Stream gaging sites were chosen to take advantage of an existing control structure (FG1) and a stabilized stream cross section (FG3). At FG1 and FG3, Q was calculated from stream stage recorded at 15-minute intervals using HOBO and Solinst pressure transducers (PT) and a stage-Q rating curve calibrated to Q measurements. Q was measured manually in the field over a range of flow conditions by the area-velocity method (AV) using a Marsh-McBirney flowmeter (Harrelson et al., 1994; Turnipseed and Sauer, 2010). ~~,~~Q measurements were not made at the highest stages recorded by the PTs, so the stage-Q rating curve at FG3 was extrapolated using

Manning's equation, calibrating Manning's n (0.067) to the Q measurements. At FG1, the flow control structure is a masonry spillway crest, so the HEC-RAS model was used to create the stage-Q relationship and calibrated to Q measurements (Brunner, 2010). See Supplementary Material B for further details on stream gaging at FG1 and FG3.

A suitable site for stream gaging was not present at the outlet of the Lower_Quarry subwatershed (FG2), so water discharge~~, SSC~~ at FG2 was calculated as the product of the specific water discharge from FG1 (m^3/km^2) and the watershed area draining to FG2 (1.17 km^2). The specific water discharge at FG2 is assumed to be the same as above FG1 since average slopes, vegetation, and soils of the watersheds are extremely similar. Discharge may be higher from the quarry surface, which represents 5.7% of the Lower_Quarry subwatershed, so Q and SSY at FG2 are conservative, lower-bound estimates, particularly during small events when specific discharge from the Upper watershed was small relative to specific discharge from the quarry. The quarry surface is continually being disturbed, sometimes with large pits excavated and refilled in the course of weeks, as well as intentional water control structures implemented over time. Given the changes in the contributing area of the quarry, estimates of water yield from the quarry were uncertain, so we assumed a uniform specific discharge for the whole ~~described in section 3.4.~~ Lower_Quarry subwatershed.

3.1.3~~.1 Objective 1: Compare~~ Suspended Sediment Concentration (SSC)

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SSC was estimated at 15 minute intervals from either 1) linear interpolation of stream water samples, or 2) turbidity data (T) recorded at 15 minute intervals and a T-SSC relationship calibrated to stream water samples. Stream water was collected by grab sampling with 500 mL HDPE bottles at FG1, FG2, and FG3. At FG2, water samples were also collected at 30 minute intervals during storm events by an ISCO 3700 Autosampler triggered by a water level sensor.

The Autosampler inlet tubing was oriented down-stream, just below the water level sensor, approximately 30 cm above the stream bed, on rebar positioned midstream. Samples were analyzed for SSC on-island using gravimetric methods (Gray, 2014; Gray et al., 2000). Water samples were vacuum filtered on pre-weighed 47mm diameter, 0.7 µm Millipore AP40 glass fiber filters, oven dried at 100 C for one hour, cooled and weighed to determine SSC (mg/L).

Interpolation of SSC from grab samples was performed if at least three samples were collected during a storm (Nearing et al., 2007), and if an SSC sample was collected within 30 minutes of peak Q. Based on low observed SSC between storm events, SSC was assumed to be zero at the beginning and end of each storm if no sample was available for those times (Lewis et al., 2001).

T was measured at FG1 and FG3 using three types of turbidimeters: 1) Greenspan TS3000 (TS), 2) YSI 600OMS with 6136 turbidity probe (YSI), and 3) two Campbell Scientific OBS500s (OBS). All turbidimeters were permanently installed in PVC housings near the streambed with the turbidity probe submerged at all flows and oriented downstream. Despite regular maintenance, debris fouling and vandalism caused frequent data loss.

A unique, linear T-SSC relationship was developed for the YSI and both OBS turbidimeters at each location using linear regression on T data and SSC samples from storm periods (r^2 values 0.79-0.99, Supplementary Material C). The T-SSC relationship can be unique to each region, stream, instrument or even each storm event (Lewis et al., 2001), and can be influenced by water color, dissolved solids~~and~~, organic matter, temperature, and particle shape, size, and composition. Despite the multiple factors relating T to SSC, T is a robust predictor of SSC in streams (Gippel, 1995), and is most accurate when a unique T-SSC relationship is developed for each instrument and field site separately, using in situ SSC samples during storms

(Lewis, 1996; Minella et al., 2008). The TS meter at FG1 was vandalized before sufficient samples had been collected to establish a T-SSC relationship for high T data, so the T-SSC relationship from the YSI was used for the TS data. Errors were higher at FG3 (RMSE 112% for YSI, 46% for OBS), and lower at FG1 (RMSE 13% for YSI at FG1). The T-SSC relationship for the YSI predicted higher SSC at FG3 than at FG1 for the same T value (Supplementary Material C), which introduces uncertainty in SSC and SSY at FG3. The impact of using the same T-SSC relationship at both FG1 and FG3 is tested in the error analysis (Section 3.2.3). The critical assumption in our application is that the parameters of the T-SSC relationship are stable over time and among storm events. The T-SSC relationships are critical to SSY calculations, so the cumulative error from these relationships were combined with other error sources to estimate uncertainty in the SSY_{EV} estimates (Section 3.2.3). See Supplementary Material C for further details on T-SSC relationships at FG1 and FG3

3.2 SSY_{EV} for disturbed and undisturbed ~~subwatersheds~~watersheds

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

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~~3.1.1. Calculation of SSY_{EV}~~

~~SSY during individual~~3.2.1 Suspended Sediment Yield during storm events (SSY_{EV})~~were~~

SSY_{EV} was calculated ~~for each sample location~~at FG1, FG2 and FG3 by integrating continuous ~~estimates of SSY, calculated from measured or modeled water discharge (Q) and measured or modeled suspended sediment concentration (SSC)~~Q and SSC (Duvert et al., 2012):

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

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^{-9}).

Storm events can be defined by ~~precipitation~~P (Hicks, 1990) or ~~discharge parameters~~Q data (Duvert et al., 2012), and the method used to identify storm events ~~on the hydrograph~~ can significantly influence the analysis of SSY_{EV} (Gellis, 2013). Due to the large number of storm events and the prevalence of complex storm events ~~recorded~~observed at the study site, we used a digital filter signal processing technique (Nathan and McMahon, 1990) in the R-statistical package EcoHydRology (Fuka et al., 2014)~~. Spurious events were sometimes identified due to instrument noise, so only events with quickflow for at least one hour and peak flow greater than 10% of baseflow were included (See Appendix C~~, which separates the hydrograph into quickflow, or direct surface or subsurface runoff that occurs during storms, and baseflow or delayed flow (Hewlett and Hibbert, 1967). Quickflow and baseflow components are not well defined in terms of hydrologic flow path; here we use the separation operationally to define storm events. Spurious events were sometimes identified due to instrument noise, so only events

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with quickflow lasting at least one hour and peak quickflow greater than 10% of baseflow were included (See Supplementary Material D for example).

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

3.~~1.~~2.2 SSY from disturbed and undisturbed portions of subwatersheds

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Land cover in the ~~LOWER~~Lower subwatersheds (Lower_Quarry and Lower_Village) includes both undisturbed forest and human-disturbed surfaces~~.~~ (Table 1). SSY_{EV} from disturbed areas only was estimated as:

$$SSY_{EV\_distrb} = SSY_{EV\_subws} - \left(sSSY_{EV\_UPPER} * Area_{undist}\right) \qquad \text{Equation 2}$$

where SSY_{EV_distrb} is SSY_{EV} from disturbed areas only (tons), SSY_{EV_subws} is SSY_{EV} (tons) measured from the subwatershed, $sSSY_{EV\_UPPER}$ is specific SSY_{EV} (tons/km^2) from the Upper subwatershed (SSY_{EV_FG1}), and $Area_{undist}$ is the area of undisturbed forest in the subwatershed (km^2). This calculation assumes that forests in all subwatersheds have SSY similar to the Upper watershed.

The disturbance ratio (DR) is the ratio of SSY_{EV} under current conditions to SSY_{EV} under pre-disturbance conditions:

$$\mathrm{DR} = \frac{SSY_{EV\_subw}}{A_{subw} * sSSY_{EV\_UPPER}} \qquad \text{Equation 3}$$

where A_{subw} is the area of the subwatershed. Both Equations ~~3~~2 and ~~4~~3 assume that $sSSY_{EV}$ from forested areas in the ~~LOWER~~Lower subwatershed equals $sSSY_{EV}$ from the undisturbed ~~UPPER~~Upper watershed~~.~~

~~*3.1.3. Relationship of sediment load to sediment budget*~~

~~We use~~ and that pre-disturbance land cover was forested throughout the ~~measured sediment yield at three locations to quantify the in-stream suspended sediment budget. Other components of sediment budgets include channel erosion and or channel and floodplain deposition (Walling and Collins, 2008). Sediment storage and remobilization can significantly complicate the interpretation of in-stream loads, and complicate the identification of a land use signal. In Faga'alu, the channel bed is predominantly large volcanic cobbles and coarse gravel, with no significant deposits of fine sediment. Upstream of the village, the valley is very narrow with no floodplain. In the downstream reaches of the lower watershed, where fines might deposit in the floodplain, the channel has been stabilized with cobble reinforced by fencing, so overbank flows and sediment deposition on the floodplain are not observed. We therefore assume that channel erosion and channel and floodplain deposition are insignificant components of the sediment budget, so the measured sediment yields at the three locations reflect differences in hillslope sediment supply. Minimal sediment storage also reduces the lag time between landscape disturbance and observation of sediment at the watershed outlet~~watershed.

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3.2.3 Error Analysis

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Uncertainty in SSY_{EV} calculations arises from errors in measured and modeled Q and SSC (Harmel et al., 2006). The root mean square error propagation method estimates the "most probable value" of the cumulative or combined error by propagating the error from each measurement and modeling procedure, i.e. stage-Q and T-SSC, to the final SSY_{EV} calculation (Topping, 1972). The resulting cumulative probable error (PE) is the square root of the sum of the squares of the maximum values of the separate errors:

$$PE = \sqrt{(E_{Qmeas}^2 + E_{SSCmeas}^2) + (E_{Qmod}^2 + E_{SSCmod}^2)} \qquad \text{Equation 4}$$

where *PE* is the cumulative probable error for SSY_{EV} estimates (±%), E_{Qmeas} is uncertainty in Q measurements (±%), $E_{SSCmeas}$ is uncertainty in SSC measurements (± %), E_{Qmod} is uncertainty in the Stage-Q relationship (RMSE, as ±% of the mean observed Q), E_{SSCmod} is uncertainty in the T-SSC relationship or from interpolating SSC samples (RMSE, as ± % of the mean observed SSC) (Harmel et al., 2009).E_{Qmeas} and $E_{SSCmeas}$ were taken from the DUET-H/WQ software tool lookup tables (Harmel et al., 2009). ~~Objective 2:~~

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The effect of uncertain SSY_{EV} estimates may complicate conclusions about anthropogenic impacts and storm metric-SSY_{EV} relationships, but difference in SSY_{EV} from undisturbed and disturbed areas was expected to be much larger than the cumulative uncertainty. High uncertainty is common in sediment yield studies where successful models estimate SSY with ±50-100% accuracy (Calhoun and Fletcher, 1999; Duvert et al., 2012). PE was calculated for SSY_{EV} from the Upper and Total watersheds, but not for the Lower subwatershed since it was calculated as the difference of SSY_{EV_UPPER} and SSY_{EV_TOTAL}.

In addition to the error due to scatter about a given T-SSC relationship, there may also be uncertainty about the regression line itself, particularly where a given instrument shows different T-SSC relationships at different locations (Supplementary Material C). In Faga'alu, the T-SSC relationship estimated higher SSC for a given T value at the disturbed site (FG3) than the forested site (FG1). In order to test for the impact of using the same T-SSC relationship at both locations, we recalculated SSY_{EV} and the disturbance ratio using the T-SSC relationship at FG3 to estimate SSC at both FG3 and FG1.

3.3 Modeling SSY_{EV} with storm metrics

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The relationship between SSY_{EV} and storm metrics ~~can be~~was modelled as a log-linear function:

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

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

Four storm metrics were tested as predictors of SSY_{EV}: Total event precipitation (Psum), event Erosivity Index (EI) (Hicks, 1990; Kinnell, 2013), total event water discharge (Qsum), and maximum event water discharge (Qmax) (Duvert et al., 2012; Rodrigues et al., 2013). The Erosivity Index describes the erosive power ~~law function:~~of rainfall and was calculated for each storm event identified in Section 3.2.1 following the methodology of Kinnell (2013) using only 1 min interval data at RG1. The discharge metrics (Qsum and Qmax) were normalized by watershed area to compare different sized subwatersheds.

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~~The regression coefficients (α and β) for the UPPER and TOTAL watersheds were tested for statistically significant differences using Analysis of Covariance (ANCOVA) (Lewis et al.,~~

~~2001).~~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} were quantified using non-parametric (Spearman) correlation coefficients. The regression coefficients (α and β) for the Upper and Total watersheds were tested for statistically significant differences using Analysis of Covariance (ANCOVA) (Lewis et al., 2001).

~~A higher intercept (α) for the human-disturbed watershed indicates higher sediment yield for the same size storm event, compared to sediment yield from the undisturbed watershed. A difference in slope (β) would indicate the relative sediment contributions from the subwatersheds change with increasing storm size.~~

3.~~3. Objective 3:~~4. Estimation of annual SSY

Annual ~~estimates of~~ SSY (mass) and sSSY (mass/area) were estimated ~~to compare Faga'alu with other watersheds reported in~~using 1) the ~~literature. A continuous~~developed storm metric-SSY_{EV} models, and 2) the ratio of annual storm precipitation to precipitation measured during storms with SSY_{EV} data.

An annual SSY time-series ~~of SSY~~ was not possible ~~at the study site~~ due to the discontinuous field campaigns and failure of or damage to the ~~instruments during some months.~~turbidimeters. Continuous records of P and Q were available for 2014, so the ~~Psum-SSY_{EV} and Qmax~~log-linear storm metric-SSY_{EV} models (Equation 5~~)~~), including log-bias correction (Duan, 2016; Ferguson, 1986), were used to predict SSY_{EV} for all storms in 2014 (Basher et al., 1997)~~. Construction of sediment mitigation structures at the quarry began in October 2014, greatly reducing SSY_{EV} from the LOWER_QUARRY subwatershed (unpublished data), so the Qmax-SSY_{EV} relationship developed prior to the mitigation was used to calculate~~

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~~the annual pre-mitigation sediment yield.~~. For storms missing Qmax data at FG3, Qmax was predicted from a linear regression between Qmax at FG1 and Qmax at FG3 for the study period (R^2 =0.88).

Annual SSY and sSSY were also estimated by multiplying SSY_{EV} from measured storms by the ratio of annual storm precipitation (P_{EVann}) to ~~the~~ precipitation ~~measured~~ during storms where SSY_{EV} was measured (P_{EVmeas}):

$$SSY_{ann} = SSY_{EV\_meas} * \frac{P_{EVann}}{P_{EVmeas}} \qquad \text{Equation 6}$$

where SSY_{ann} is estimated annual SSY from storms, SSY_{EV_meas} is SSY_{EV} from sampled storms (all, Tables 2 and 4), P_{EVann} is the precipitation during all storm events in a year, and P_{EVmeas} is precipitation during the set of sampled storms. Equation 6 assumes that the sediment yield per mm of storm precipitation is constant over the year, and ~~that~~insensitive to the size distribution of storms ~~has no effect on SSY_{EV}~~, though there is ~~some~~ evidence that SSY_{EV} increases exponentially with storm size (Lewis et al., 2001; Rankl, 2004). Equation 6 also ignores sediment yield during non-storm periods, which is justified by the low SSC (typically under 20 mg/L) and Q (baseflow) observed between storms.

~~**3.4. Field Data Collection**~~

~~Data on precipitation (P), water discharge (Q), suspended sediment concentration (SSC) and turbidity (T) were collected during four field campaigns: January-March 2012, February-July 2013, January-March 2014, and October-December 2014, and several intervening periods of unattended monitoring by instruments with data loggers. Field sampling campaigns were scheduled to coincide with the period of most frequent storms in the November-May wet season, though large storms were sampled throughout the year.~~

~~*3.4.1. Precipitation (P)*~~

~~P was measured at three locations in Faga'alu watershed using Rainwise RAINEW tipping-bucket rain gages (RG1 and RG2) and a Vantage Pro Weather Station (Wx) (Figure 1). Data at RG2 was only recorded January-March, 2012 to determine a relationship between elevation and precipitation in the LOWER subwatershed. The total event precipitation (Psum) and event Erosivity Index (EI30) were calculated using data from RG1, with data gaps filled by 15 minute interval precipitation data from Wx.~~

~~*3.4.2. Water Discharge (Q)*~~

~~Stream gaging sites were chosen to take advantage of an existing control structure (FG1) and a stabilized stream cross section (FG3) (Duvert et al, 2010). At FG1 and FG3, Q was calculated from stream stage measurements taken at 15 minute intervals using HOBO pressure transducers (PT) and a stage-Q rating curve calibrated to manual Q measurements. Q was measured manually in the field under both baseflow and stormflow conditions by the area-velocity method (AV) using a Marsh-McBirney flowmeter (Harrelson et al., 1994; Turnipseed and Sauer, 2010). The PTs recorded stages that exceeded the highest stage with manually-measured Q, so the stage-Q rating at FG3 was extrapolated using Manning's equation, calibrating Manning's n (0.067) to the Q measurements. At FG1, the flow control structure is a masonry spillway crest of a defunct stream capture. The highest stage recorded by the PT (120 cm) exceeded the highest stage with manually-measured Q (17 cm), and the flow structure did not meet the assumptions for using Manning's equation to predict flow, so the HEC-RAS model was used to create the stage-Q relationship (Brunner, 2010). See Appendix B for details of the cross sections and rating curves.~~

~~A suitable site for stream gaging was not present at the outlet of the LOWER_QUARRY subwatershed (FG2), so water discharge at FG2 was calculated as the product of the specific water discharge from FG1 (m^3/0.9 km^2) and the watershed area draining to FG2 (1.17 km^2). This assumes that specific water discharge from the subwatershed above FG2 is similar to above FG1. Discharge may be higher from the quarry surface, which represents 5.7% of the LOWER_QUARRY subwatershed, so Q and SSY at FG2 are conservative, lower bound estimates, particularly during small events when specific discharge from the UPPER watershed was small relative to specific discharge from the quarry. The quarry surface is continually being disturbed, sometimes with large pits excavated and refilled in the course of weeks, as well as intentional water control structures implemented over time. Given the changes in the contributing area of the quarry, estimates of water yield from the quarry were uncertain, so we assumed a uniform specific discharge for the whole LOWER_QUARRY subwatershed.~~

~~*3.4.3. Suspended Sediment Concentration (SSC)*~~

~~SSC was estimated at 15 minute intervals from either 1) linear interpolation of SSC measured from water samples, or 2) turbidity data (T) recorded at 15 minute intervals and a T-SSC relationship calibrated to stream water samples collected over a range of Q and SSC. Stream water samples were collected by grab sampling with 500 mL HDPE bottles at FG1, FG2, and FG3. At FG2, water samples were also collected at 30 min intervals during storm events by an ISCO 3700 Autosampler triggered by a stage height sensor. Samples were analyzed for SSC on-island using gravimetric methods (Gray, 2014; Gray et al., 2000). Water samples were vacuum filtered on pre-weighed 47mm diameter, 0.7 um Millipore AP40 glass fiber filters, oven dried at 100 C for one hour, cooled and weighed to determine SSC (mg/L).~~

~~Interpolation of SSC values from grab samples was performed if at least three stream water samples were collected during a storm event (Nearing et al., 2007), and if an SSC sample was collected within 30 minutes of peak Q. SSC was assumed to be zero at the beginning and end of each storm if no grab sample data was available for those times (Lewis et al., 2001).~~

~~Turbidity (T) was measured at FG1 and FG3 using three types of turbidimeters: 1) Greenspan TS3000 (TS), 2) YSI 600OMS with 6136 turbidity probe (YSI), and 3) Campbell Scientific OBS500 (OBS). All turbidimeters were permanently installed in protective PVC housings near the streambed where the turbidity probe would be submerged at all flow conditions, with the turbidity probe oriented downstream. Despite regular maintenance, debris fouling during storm and baseflows was common and caused data loss during several storm events (Lewis et al., 2001).The T-SSC relationship can be unique to each region, stream, instrument or even each storm event (Lewis et al., 2001), and can be influenced by water color, dissolved solids and organic matter, temperature, and the shape, size, and composition of sediment. However, T has proved to be a robust surrogate measure of SSC in streams (Gippel, 1995), and is most accurate when a unique T-SSC relationship is developed for each instrument separately, using in situ grab samples under storm conditions (Lewis, 1996). A unique T-SSC relationship was developed for each turbidimeter, at each location, using T data and SSC samples from storm periods only (r^2 values 0.79-0.99). See Appendix D for details on the T-SSC relationships.~~

~~*3.4.4. Cumulative Probable Error (PE)*~~

~~Uncertainty in SSY_{EV} estimates arises from both measurement and model errors, including stage-Q and T-SSC (Harmel et al., 2006). The Root Mean Square Error (RMSE) method estimates the "most probable value" of the cumulative or combined error by propagating~~

~~the error from each measurement and modeling procedure to the final SSY_{EV} calculation (Topping, 1972). The resulting cumulative probable error (PE) is the square root of the sum of the squares of the maximum values of the separate errors:~~

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

4. Results

4.1 Field Data Collection

4.1.1 Precipitation ~~and discharge~~

~~Annual precipitation (P) measured at RG1 was 3,502 mm, 3,529 mm, and 3,709 mm in 2012, 2013, and 2014, respectively, which averages 94% of long-term precipitation (=3,800 mm) from PRISM data (Craig, 2009). 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 annual P of 3,000-4,000 mm on the lowlands, increasing to~~

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~~more than 6,350 mm at high elevations (>400 m.a.s.l.) (Craig, 2009; Dames & Moore, 1981; Wong, 1996). P data measured at higher elevations would be useful to determine the orographic effect. For this analysis, however, the absolute values of P in each subwatershed are not important since P and the erosivity index are only used as predictive storm metrics for Objective 2.~~

At RG1, P was 3,502 mm, 3,529 mm, and 3,709 mm in 2012, 2013, and 2014, respectively, which averages 94% of long-term P (=3,800 mm) (PRISM data; Craig, 2009). Daily P at RG1 was similar to P at Wx (regression slope=0.95, r^2=0.87) and at RG2 (slope=0.75, r^2=0.85). Higher P was expected at higher elevation at RG2 so lower P at RG2 was assumed to be caused by measurement error, as the only available sampling location was a forest clearing with high surrounding canopy. P measured at higher elevations would be useful to determine the orographic effect, but for this analysis the absolute values of P in each subwatershed are not as important since P and the Erosivity Index are only used as predictive storm metrics. Given the near 1:1 relationship between daily P measured at RG1 and Wx, P was assumed to be homogenous over the Lower subwatershed.

4.1.2 Water Discharge (Q)

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

< Figure 3 here please>

4.~~2 Objective~~ 1~~: Compare SSC and SSY_{EV} for disturbed and undisturbed subwatersheds~~

~~4.2.1.~~3 Suspended ~~sediment concentrations~~Sediment Concentrations (SSC) during storm and non-storm periods

<Figure 4 here please>

~~SSC was consistently lowest downstream of the forested watershed (FG1),~~An example of a storm event on 2/14/2014 (Figure 4) shows that SSC at FG2 was highest on the rising limb of the hydrograph, and that T and SSC at FG3 were always higher than at FG1. SSC was consistently lowest at FG1, highest downstream of the quarry (FG2), and intermediate downstream of the village (FG3), during both storm and non-storm periods (Figure 5a, 5b). ~~A single storm event from 2/14/2014 (Figure 4) shows that SSC was highest at FG2 on the rising limb of the hydrograph, and that turbidity and SSC at FG3 were always higher than at FG1 throughout the storm event. Mean (μ) and maximum SSC of all water samples, including those collected during both storm and non-storm periods,~~Mean and maximum SSC of all stream water samples were lowest at FG1 (μ=28 mg/L, max=500 mg/L, n=59), highest at FG2 (μ=337 mg/L, max=12,600 mg/L, n=90~~ grab samples, n=198 from the Autosampler~~), and intermediate at FG3 (μ=148 mg/L, max=3,500 mg/L, n=159). ~~SSC collected during non-storm periods were lowest at FG1, highest at FG2 (n=21), and in between at FG3 (n=45) (Figure 5a). Similarly, SSC during storms was highest at FG1 (n=45), highest at FG 2, (n=69) and intermediate at FG3 (n=120).~~ SSC data ~~collected~~ at FG1~~, FG2 and FG3~~-3 were ~~highly~~ non-normal, so non-parametric ~~tests for statistical~~ significance tests were applied. SSC was ~~statistically~~ significantly different among the three ~~sampled sites~~sites during non-storms ~~($p<10^{-4}$)~~ and storms ($p<10^{-4}$). Pair-wise Mann-Whitney tests between FG1 and FG2 were significant ($p<10^{-4}$ for both storms and non-storms~~), but~~

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~~between~~). FG2 and FG3 were ~~significant~~significantly different for non-storm periods ($p<0.05$) but not for storms ($p>0.10$~~).~~) due to the high variance.

<Figure 5 here please>

SSC varied by several orders of magnitude for a given Q at FG1~~, FG2, and FG3~~-3 (Figure 6) due to significant hysteresis observed during storm periods (Figure 4~~, 6). At FG1, variability of SSC during stormflow was assumed to be caused by randomly occurring landslides or mobilization of sediment stored in the watershed during large storm events. The maximum~~). Maximum SSC at FG1 (500 mg/L~~),~~,) was sampled on 04/23/2013 at high ~~discharge~~Q (Q_{FG1}= 3,724 L/sec) (Figure 6a). ~~Anecdotal and field observations reported higher than normal SSC upstream of the quarry during the 2013 field season, possibly due to landsliding from previous large storms (G.~~Maximum SSC at ~~Poysky, pers. comm.).<Figure 6 here please>~~

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

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

~~Given the close proximity of the quarry to the stream, SSC downstream of the quarry can be highly influenced by mining activity like rock extraction, crushing, and/or hauling operations. During 2012, a common practice for removing fine sediment from crushed aggregate was to rinse it with water pumped from the stream. In the absence of retention structures the fine sediment was discharged directly to Faga'alu stream, causing high SSC during non-storm periods with no P in the preceding 24 hours (solid symbols, Figure 6b-c).~~ <Figure 6 here please>

~~Riverine discharge of fine sediment rinsed from aggregate was discontinued in 2013. In 2013 and 2014, waste sediment was piled on-site and severe erosion of these changing stockpiles caused high SSC only during storm events.~~

4.2.~~2. Suspended sediment yield during storm events (SSYEV)~~ SSY$_{EV}$ for disturbed and undisturbed watersheds

A total of 210 ~~storm events~~storms were identified ~~using hydrograph separation on the Q data at FG1 and FG3 between~~ January, 2012, ~~and~~to December, 2014. A total of 169 ~~events~~storms had simultaneous Q data at FG1 and FG3 (~~Appendix C~~Supplementary Material D, Table 1). SSC data ~~from T or interpolated grab samples~~ were recorded during 112 (FG1) and 74 ~~events~~storms (FG3). Of those storms, 42 ~~events~~ had ~~data for~~simultaneous P, Q, and SSC data at ~~both~~ FG1 and FG3. ~~SSY data from interpolated grab samples were collected at FG2 for~~Of those storms, only 8 ~~storms to calculate SSY$_{EV}$ from the LOWER_QUARRY and LOWER_VILLAGE subwatersheds separately.~~had simultaneous P, Q, and SSC data at FG2. Storm ~~event durations~~events ranged from 1 hour to 2 days, with mean duration of 13 hours.

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4.2.1 Suspended sediment yield during storm events (SSY_{EV}) from Upper, Lower, and Total watersheds

For the 42 storms with ~~complete~~P, Q, and SSC data at both FG1 and FG3~~ (Table 2),~~, SSY_{EV_TOTAL} was 129±121 tons, with 17±7 tons from the ~~UPPER subwatershed~~ Upper watershed and 112 tons from the ~~LOWER~~Lower subwatershed~~.~~ (Table 2). The ~~UPPER~~Upper and ~~LOWER~~Lower subwatersheds are similar in size (0.90 km² and 0.88 km²) but SSY_{EV_LOWER} accounted for 87% of SSY_{EV} at the watershed outlet~~ (Table 2).~~. The DR ~~estimated using~~ (Equation 4, ~~with~~ $sSSY_{EV\_}$~~UPPER~~Upper = 18.8 tons/km~~²,~~²) suggests $sSSY_{EV}$ has increased by 6.8x in the ~~LOWER~~Lower subwatershed, and 3.9x for the ~~TOTAL~~Total watershed compared with undisturbed forest in the Upper watershed.

<Table 2 here please>

~~Disturbed areas accounted for 10% of the LOWER~~4.2.2 SSY from disturbed and undisturbed portions of Upper, Lower, and Total watersheds

In the Lower subwatershed~~ area~~, disturbed areas cover 10% of the surface but ~~approximately~~contributed 87% of ~~the~~ SSY_{EV}~~ from~~ $_{LOWER}$. In the ~~LOWER subwatershed.~~ ~~Only~~Total watershed, disturbed areas cover only 5.2% of the ~~TOTAL watershed area was disturbed,~~surface but ~~SSY from disturbed areas accounted for~~contributed 75% of SSY_{EV_TOTAL}. sSSY from disturbed areas in the ~~LOWER~~Lower subwatershed was 1,095 tons/km², or 58x the sSSY of undisturbed forest (Table 3).

<Table 3 here please>

~~The separate contributions to SSY from the quarry and village were determined for eight~~4.2.3 Suspended sediment yield during storm events (~~Table 4), where~~ SSY$_{EV}$) from Lower_Quarry and Lower_Village watersheds

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For the 8 storms with P, Q, and SSC data at FG1-3, sSSY from the Upper, Lower_Quarry, Lower_Village, and the Total watershed was 15, 61, 27, and 26 tons/km², respectively, with 29% of SSY$_{EV}$ ~~came~~ from the ~~UPPER~~Upper subwatershed, 36% from the ~~LOWER_QUARRY~~Lower_Quarry subwatershed, and 35% from the ~~LOWER_VILLAGE~~Lower_Village subwatershed. ~~sSSY from the UPPER, LOWER_QUARRY, and LOWER_VILLAGE subwatersheds, and the TOTAL watershed was 15, 61, 27, and 26 tons/km², respectively.~~ The storms in Table 4 may underrepresent the contributions of the quarry and village to SSY, since they show a ~~smaller increase in SSY from~~lower DR for the ~~TOTAL~~Total watershed (1.7x SSY$_{UPPER}$) compared with the 42 storms ~~with data at FG1 and FG3~~in Table 2 (3.9x SSY$_{UPPER}$ ~~Table 2), so these storms may underrepresent the contributions of the quarry and village to SSY.~~). sSSY increased by 4.1x in the ~~LOWER_QUARRY~~Lower_Quarry subwatershed and 1.8x in the ~~LOWER_VILLAGE~~Lower_Village subwatershed compared with the undisturbed ~~UPPER~~Upper watershed.

<Table 4 here please>

*~~Very~~*4.2.4 SSY from disturbed and undisturbed portions of *Lower_Quarry* and *Lower_Village* *watersheds*

Disturbed areas cover small fractions of the ~~subwatershed areas are disturbed~~subwatersheds, yet contributed roughly 77% of SSY $_{EV\_LOWER\_QUARRY}$ (6.5% disturbed) and 51% of SSY $_{EV\_LOWER\_VILLAGE}$ (11.7% disturbed~~) subwatersheds was from~~). Similarly, disturbed areas~~. Similarly,~~ cover 5.2% of the ~~TOTAL~~Total watershed ~~was disturbed~~ but contributed 75-45% of SSY $_{EV\_TOTAL}$ ~~was from disturbed areas~~ (Tables 3 and 5). ~~The quarry significantly increased SSY and contributed the majority of SSY from disturbed areas in Faga'alu watershed.~~ sSSY from disturbed areas in the ~~UPPER~~Upper (37 tons/km²), ~~LOWER_QUARRY~~Lower_Quarry (722 tons/km²), and ~~LOWER_VILLAGE~~Lower_Village subwatersheds (116 tons/km²) suggested that disturbed areas increase sSSY over forested conditions by 49x and 8x in the ~~LOWER_QUARRY~~Lower_Quarry and ~~LOWER_VILLAGE~~Lower_Village subwatersheds, respectively. Human disturbance in the ~~LOWER_VILLAGE~~Lower_Village subwatershed ~~also~~ increased ~~SSY~~SSY_{EV} above natural levels but the magnitude of disturbance was much lower than the quarry.

<Table 5 here please>

4.2.~~3 Cumulative Probable~~5 Error ~~(PE)~~analysis

Cumulative Probable ~~Error (RMSE %) for~~Errors (PE) in SSY_{EV} ~~estimates were~~, calculated from ~~the~~ measurement ~~errors for Q (8.5%) and SSC grab samples (16.3%), and the~~ and model errors ~~of the respective stage-Q and T-SSC relationships for that location. Cumulative Probable Errors (PE) in SSY_{EV} were 28-49~~in Q and SSC data, were 40-56% (μ=~~43~~52%) at FG1 and 36-118% (μ=94%) at FG3.

The measurement error ~~(RMSE)~~ for Q at FG1 and FG3 was 8~~.5 %, which included error in the~~%, including area-velocity measurements (6%), continuous Q measurement in a natural channel (6%), pressure transducer error (0.1%), and streambed condition (firm, stable bed=0%) (DUET-H/WQ look-up table (Harmel et al., 2006)). ~~The model~~Model errors ~~(RMSE)~~ were 32% for the stage-Q rating curve using Manning's equation at FG3, and 22% using HEC-RAS at FG1.

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The measurement error ~~(RMSE)~~ for SSC was 16~~.3%, which included errors for sample collection and analysis. Sample collection error consisted of~~ %, including interpolating over a 30 min interval (5~~%) and~~%), sampling during stormflows (3~~%). Sample analysis error was from~~ %), and measuring SSC by filtration (3.9~~%). The model errors (RMSE)~~ %) (DUET-H/WQ look-up table (Harmel et al., 2006)). Model errors of the T-SSC relationships were ~~16% (4~~13% (3 mg/L) for the YSI and TS turbidimeters at FG1, ~~113% (348~~112% (342 mg/L) for the YSI turbidimeter at FG3, and 47% (46~~% (48~~ mg/L) for the OBS turbidimeter at FG3.

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

4.3 ~~Objective 2:~~ Modeling SSY_{EV} with storm metrics

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4.3.1~~.~~ Selecting the best predictor of SSY_{EV}

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Qsum and Qmax were the best predictors of SSY_{EV} for the forested ~~UPPER~~Upper watershed, and ~~Psum and~~ Qmax ~~were~~was the best predictors for the ~~TOTAL~~Total watershed~~.~~ (Figure 7, Table 6). SSY_{EV} is calculated from Q so it is expected that Qsum ~~should correlate~~correlated closely with SSY_{EV} (Duvert et al., 2012; Rankl, 2004). Discharge metrics were ~~also~~ highly correlated with SSY_{EV} in the ~~TOTAL~~Total watershed, suggesting ~~discharge~~

~~metrics~~they are good predictors in both disturbed and undisturbed watersheds. Most of the scatter in the Qmax-SSY_{EV} relationship is observed for small events, and Qmax correlated strongly with the largest SSY_{EV} values, when most of the annual ~~sediment load~~SSY is generated (~~Table 6~~Figure 7a).

<Table 6 here please>

4.3.2. Effect of event size and watershed disturbance

~~<Table 6 here please>~~

~~Precipitation was measured at the quarry, which may reflect precipitation characteristics more accurately in the LOWER than the UPPER watershed, and account for the lower correlation coefficients between precipitation and~~In general, $SSY_{EV\_}$~~$_{UPPER}$. SSY from the LOWER subwatershed is hypothesized to be mostly generated by hillslope erosion by sheetwash and rill formation at the quarry and on dirt roads, and agricultural plots, whereas SSY from the UPPER subwatershed is hypothesized to be mainly from channel processes and mass wasting. Mass wasting can contribute large pulses of sediment which can be deposited near or in the streams and entrained at high discharges during later storm events. Given the high correlation coefficients between SSY_{EV} and Qmax in both watersheds, Qmax may be a promising predictor that integrates both precipitation and discharge processes.~~

~~*4.3.2. Effect of event size and watershed disturbance*~~

~~SSY_{EV} from the~~ $_{TOTAL}$ ~~watershed~~ was higher than ~~from the~~ SSY_{EV_UPPER} ~~watershed~~ for the full range of measured storms with the exception of a few events~~ that are considered outliers.~~. The outlier events could be ~~attributed to~~ from measurement error or ~~to landslides or other~~ mass movements in the Upper watershed. The event with much higher SSYEV at FG1 (Figure 7d) did not have corresponding data for FG2 or FG3, to determine if this event was data error. The

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separation of multi-peak storm events, storm sequence, and antecedent conditions may also play a role. ~~UPPER subwatershed.~~ ~~The separation of multi-peak storm events, storm sequence, and antecedent conditions may also play a role.~~ While ~~the climate on Tutuila is tropical, without~~ strong seasonality~~, periods of~~ is not observed in Faga'alu, low rainfall can persist for several weeks, perhaps altering ~~the~~ water and sediment dynamics in ~~the~~ subsequent storm events.

<Figure 7 here please>

~~All~~A higher intercept (α) for the human-disturbed compared to the undisturbed watershed indicates higher SSY_{EV} for the same size storm event. A difference in slope (β) indicates the relative subwatershed contributions vary with storm size. All storm metric-SSY_{EV} model intercepts (α) were significantly different (p<0.01), but only the Qsum-SSY_{EV} model showed significantly different slopes (β, p<0.01~~). The Qsum-SSY_{EV} models indicate that SSY_{EV} from the UPPER and TOTAL watersheds converge at higher Qsum values. Conversely, the Psum- and Qmax-SSY_{EV} models show no change in relative contributions of SSY over the range of storm sizes (Figure 7).~~

~~<Figure 7 here please>~~

) (Figure 7, Table 6). The relative sediment contribution ~~of SSY~~ from the human-disturbed watershed was hypothesized to diminish with increasing storm size~~. The~~, but the results from ~~precipitation metrics~~P and ~~discharge~~Q metrics were contradictory. ~~The~~ The Qsum-SSY_{EV} model indicates a decrease in relative contribution ~~of SSY_{EV}~~ from the ~~human-~~disturbed Lower watershed~~ decreases with storm size in the Qsum-SSY_{EV} model~~, but the Psum- and Qmax-SSY_{EV} models show no change ~~in relative contributions~~ over increasing storm size (Figure 7). It was hypothesized that SSY_{EV} from undisturbed forest ~~areas~~ would become the dominant source for larger ~~storm events~~storms, but the DR remains high for large ~~storm~~

~~events~~storms due to ~~the~~ naturally low SSY_{EV} from ~~natural~~ forest areas in Faga'alu watershed. This suggests that disturbed areas were not supply limited for the range of sampled storms.

~~This suggests that disturbed areas were not supply limited for the range of sampled storms.~~

4.~~4.4 Objective 3:~~ Estimation of annual SSY

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~~Estimates of annual sSSY depended~~Annual SSY estimates varied, depending on which ~~predictor~~storm metric or set of storms (all, Table 2, Table 4) was used ~~to estimate SSY_{EV}.~~. The Qmax models (with bias correction) and Equation 6 using all events gave different annual SSY estimates at both the Upper watershed (41-129 tons/yr) and the Total watershed (655-428 tons/yr). The Psum model resulted in ~~a~~ much lower ~~estimate of sSSY than the Qmax model (Table 7). The large difference in sSSY between the two methods was~~estimates due to higher scatter about the Psum-SSY_{EV} relationship for large events, even with bias correction, compared with the more robust Qmax-SSY_{EV}~~, and the Qmax~~ model ~~is likely more robust. Annual SSY was also calculated~~(Table 7). The Qmax-SSY_{EV} model prediction is sensitive to the storm-size distribution, with significantly more SSY_{EV} for ~~2014~~events with higher Qmax. Comparing annual SSY estimates from different methods, using ~~Equation 6 for three~~different sets of storm ~~events: a) all events with SSY_{EV} data, including those where SSY_{EV} data were only available for a single site; b) only events where data was available for both UPPER (FG1) and TOTAL (FG3) and c) only events where data was available for UPPER (FG1), LOWER_QUARRY (FG2), and TOTAL (FG3). Including all storms (method a) will provide~~sizes can therefore make it appear that there is much disagreement when in fact this variability arises mostly from the ~~best estimate at a given location, while b) and c) allow more direct comparison of different subwatersheds.~~ variation in storm size distribution.

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<Table 7 here please>

Annual storm precipitation (P_{EVann}) in 2014 was 2,770 mm, representing 69% of total annual precipitation (3,709 mm). The remaining 31% of precipitation did not result in a rise in stream level sufficient to be classified as an event with the ~~<Table 7 here please>~~

~~Annual storm precipitation (P_{EVann}) in 2014 was 2,770 mm, representing 69% of total annual precipitation (3,709 mm). The remaining 31% of precipitation did not result in a rise in stream level sufficient to be classified as an event with the hydrograph separation~~ method used here. All storms with measured SSY_{EV} ~~at FG1~~ $_{UPPER}$ from 2012-2014 included 3,457 mm of precipitation (P_{EVmeas}), or 125% of P_{EVann}, so estimated annual ~~SSY from the UPPER subwatershed from~~ SSY_{UPPER} (Equation 6) was 41 tons/yr (45 tons/km²/yr). All storms with measured SSY_{EV} ~~at FG3~~ $_{TOTAL}$ from 2012-2014 included 2,628 mm of precipitation, or 95% of expected annual storm precipitation so estimated annual ~~SSY from the TOTAL watershed~~ SSY_{TOTAL} was 428 tons/yr (241 tons/km²/yr).

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

5. Discussion

~~5. Discussion~~

5.1 ~~Objective 1: Compare~~ SSC and SSYEV for disturbed and undisturbed ~~subwatersheds~~watersheds

~~*Event wise analysis of SSY_{EV} was useful because hysteresis*~~*5.1.1 SSC for disturbed and ~~interstorm~~undisturbed watersheds in Faga'alu*

At FG1, SSC variability during storms was assumed to be caused by landslides or channel erosion (including previous landslides) (Figure 6a). Anecdotal and field observations reported unusually high SSC at FG1 during 2013, possibly from landsliding during previous large storms (G. Poysky, pers. comm.).~~significant scatter in~~ At FG2 and FG3, additional variability in the ~~instantaneous~~ Q-SSC relationship~~. While~~ was caused by changing sediment availability from quarrying operations and construction in the ~~instantaneous Q-SSC relationship illustrated large increases in SSC~~ village. High SSC values observed downstream of the quarry~~,~~ ~~the hysteresis and interstorm variability meant~~ (FG2) during low Q were caused by two mechanisms: 1) P that ~~a single Q~~ generated high SSC ~~relationship could~~runoff but did not ~~be used to estimate sediment loading, which complicated detection of human impact~~result in storms identified on the hydrograph, and 2) washing fine sediment ~~concentrations and yields.~~ into the stream during quarry operations.

Given the close proximity of the quarry to the stream, SSC at FG2 was highly influenced by mining activity like rock extraction, crushing, and/or hauling operations. During 2012, a common practice for removing fine sediment from crushed aggregate was to rinse it with water pumped from the stream. In the absence of retention structures the fine sediment was discharged

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directly to Faga'alu stream, causing high SSC during non-storm periods with no P in the preceding 24 hours (solid symbols, Figure 6b-c). ~~Measurement of SSY_{EV} allows comparison of similar size storms to determine change over space and time without problems of interannual variability in precipitation totals. The simple regression models that predict annual sediment load from either precipitation or stormflow measurements eliminate the need for long-term field work to estimate annual total yields. From a management perspective, the event-wise approach to estimating human impacts on sediment is less expensive than efforts to measure annual yields since it does not require a complete year of monitoring, and can be rapidly conducted if mitigation or disturbance activities are already planned. With predictive models of SSY_{EV} that are based on an easily-monitored storm metric like maximum event discharge, SSY_{EV} can be modeled to compare with either post-mitigation or post-disturbance SSY_{EV}.~~

In 2013 and 2014, riverine discharge or rinsed sediment was discontinued, and sediment was piled on-site where severe erosion of these changing stockpiles caused high SSC only during storm events.

5.~~2 Objective~~ 1.2 Compare SSY_{EV} with other kinds of sediment disturbance

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SSY at Faga'alu was 3.9x higher than the natural background. Studies in similar watersheds have documented one to several orders of magnitude increases in SSY from land use that disturbs a small fraction of the watershed area (Stock et al., 2010). Urbanization (construction-phase) and mining can increase SSY by two to three orders of magnitude in catchments of several km², exceeding yields from the most unstable, tectonically active natural environments of Southeast Asia (Douglas, 1996). In three basins on St. John, US Virgin Islands unpaved roads increased sediment delivery rates by 3-9 times (Ramos-Scharrón and Macdonald, 2005). Disturbances at larger scales in other coral reef areas have been similar to Faga'alu, such as the Great Barrier Reef (GBR) catchment (423,000 km^2) where SSY increased by a factor of 5.5x since European settlement (Kroon et al., 2012). Mining has been a major contributor of sediment in other watersheds on volcanic islands with steep topography and high precipitation, increasing sediment yields by 5-10 times in a watershed in Papua New Guinea (Hettler et al., 1997; Thomas et al., 2003). In contrast to other land disturbances like fire, logging, or urbanization where sediment disturbance decreases over time, the disturbance from mining is persistently high. Disturbance magnitudes are similar to the construction phase of urbanization (Wolman and Schick, 1967), or high-traffic unpaved roads (Reid and Dunne, 1984), but persist or even increase over time.

While unpaved roads are often a major sediment source in humid forested regions (Lewis et al., 2001; Ramos-Scharrón and Macdonald, 2005; Reid and Dunne, 1984), most roads in the urban area in Faga'alu were stabilized with aggregate and not generating significant amounts of sediment. Other disturbances in Faga'alu included a few small agricultural plots, small construction sites and bare dirt on roadsides. Repeated surface disturbance at the quarry is a key process maintaining high rates of sediment generation.

Annual sSSY from the quarry was estimated from Equation 6 and sSSY from disturbed area in the Lower_Quarry (Table 5) to be approximately 6,700 tons/km^2/yr. The quarry surfaces are comprised of haul roads, piles of overburden, and steep rock faces which can be described as a mix of unpaved roads and cut-slopes. sSSY from cutslopes varies from 0.01 tons/km^2/yr in Idaho (Megahan, 1980) to 105,000 tons/km^2/yr in Papua New Guinea (Blong and Humphreys, 1982), so the sSSY ranges measured in this study are well within the ranges found in the literature.

~~:~~5.2 Modeling SSY_{EV} with storm metrics

Similar to other studies, the highest correlations with SSY_{EV} at Faga'alu were observed for discharge metrics Qsum and Qmax (Basher et al., 2011; Duvert et al., 2012; Fahey et al., 2003; Hicks, 1990; Rankl, 2004; Rodrigues et al., 2013). Given the high correlation coefficients between SSY_{EV} and Qmax in both watersheds, Qmax may be a promising predictor that integrates both precipitation and discharge processes in diverse watersheds.

In Faga'alu, SSY_{EV} was least correlated with the EI. Rodrigues et al. (2013) hypothesized that EI is poorly correlated with SSY_{EV} due to the effect of previous events on antecedent moisture conditions and in-channel sediment storage. Cox et al. (2006) found EI was more correlated with soil loss in an agricultural watershed than a forested watershed, and Faga'alu is mainly covered in dense forest. P was measured near the quarry (RG1), which may reflect precipitation characteristics more accurately in the Lower than the Upper watershed, and account for the lower correlation coefficients between SSY_{EV_UPPER} and Psum and EI. SSY_{LOWER} was hypothesized to be generated by sheetwash and rill formation at the quarry and agricultural plots, whereas SSY_{UPPER} was hypothesized to be from channel processes and mass wasting. Mass wasting can contribute large pulses of sediment which can be deposited near or in the streams and entrained at high discharges during later storm events. ~~Several researchers have attempted to explain values of the intercept (α) and slope (β) coefficients of the~~

The Q-SSC relationship (sediment rating curve) coefficients have no physical meaning, but the intercept (α) and slope (β) can be interpreted as a function of watershed characteristics~~. 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). Similarly, Rankl (2004) hypothesized that the intercept in the Qmax-

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SSY_{EV} relationship varied with the watershed's sediment availability and erodibility ~~in watersheds~~. While slopes in log-log space can be compared directly (Duvert et al., 2012), intercepts must be plotted in similar units~~, and normalized by watershed area. In five semi-arid to arid watersheds (2.1-1,538 km²) in Wyoming, United States~~ and normalized by watershed area. Most studies do not correct storm metric-SSY models for log-bias, as is suggested by Ferguson (1986) for Q-SSC relationships, so we calculated the bias correction factor separately from the intercept (Equation 5) to compare our model slopes and intercepts with these other studies. In five semi-arid to arid watersheds (2.1 - 1,538 km²) in Wyoming, United States, Qmax- SSY_{EV} relationship intercepts ranged from 111 - 4,320 (Qmax in m³/s/km², SSY_{EV} in Mg/km²) (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 km~~²)~~²), intercepts ranged from 25-5,039 (Duvert et al., 2012)~~, the intercepts ranged from 25-5,039.~~. In Faga'alu, ~~the intercept~~intercepts were 0.4 and 2.4 in the undisturbed~~, UPPER subwatershed was 0.35, and in the~~ and disturbed~~, TOTAL watershed the intercept was 1.38, which~~ watersheds, respectively. These intercepts are ~~an order~~1-2 orders of magnitude ~~or two~~ lower than ~~the lowest intercepts~~ in Rankl (2004) and Duvert et al. (2012)~~. This suggests~~, suggesting that sediment availability is relatively low ~~in Faga'alu,~~ under natural and human-disturbed conditions in Faga'alu, likely due to the dense forest cover.

High slope values in the log-log plots (β coefficient) suggest that small ~~changes~~increases in stream discharge ~~lead to~~correlate with large increases in sediment load due to the erosive power of the ~~river~~stream or the availability of new sediment sources at high Q (Asselman, 2000). Rankl (2004) assumed that the slope was a function of rainfall intensity on hillslopes~~,~~ and found that the slopes ~~ranged from 1.07-1.29 in five semi-arid to arid watersheds in Wyoming, and~~ were not statistically different among watersheds~~.~~ and ranged from 1.07-1.29 in semi-arid Wyoming. In~~ the~~ watersheds in Duvert et al. (2012), slopes ranged from 0.95-1.82, and from 1.06-2.45 in eighteen other watersheds (0.60-1,538 km²) in diverse geographical settings (Basher et al., 1997; Fahey and Marden, 2000; Hicks et al., 2009; Rankl, 2004; Tropeano, 1991)~~ compiled by Duvert et al. (2012). In Faga'alu, slopes were 1.51 and 1.40 in the UPPER and TOTAL watersheds, respectively. These slopes are very consistent with the slopes presented~~. In Faga'alu, slopes were 1.51 and 1.41 in the undisturbed and disturbed watersheds, respectively. These slopes are consistent with the slopes in Rankl (2004) and Duvert et al. (2012), despite large differences in climate and land cover.

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

5.3 ~~Objective 3: ~~Estimation of annual SSY~~ and~~: comparison with other tropical islands

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Sediment yield is highly variable among~~ individual~~ watersheds, but is generally controlled by climate, vegetation cover, and geology, with human disturbance playing an increasing role in the 20th century (Syvitski et al., 2005). Sediment yields in tropical Southeast Asia and high-standing islands between Asia and Australia range from ~10 tons/km^2/yr in the granitic Malaysian Peninsula to ~10,000 tons/km^2/yr in the tectonically active, steeply sloped island of Papua New Guinea (Douglas, 1996). Sediment yields from Faga'alu are on the lower end of the range, with sSSY of 45-~~68~~143 tons/km^2/yr from the undisturbed ~~UPPER~~Upper watershed, and 241-~~247~~368 tons/km^2/yr from the disturbed ~~TOTAL~~Total watershed~~.~~ (estimated from Qmax model with bias correction and Equation 6 with all events).

Milliman and Syvitski (1992) report high average sSSY (1,000-3,000 tons/km^2/yr) from watersheds (10-100,000 km^2) in tropical Asia and Oceania~~, though their~~. Their regional models of sSSY as a function of basin size and maximum elevation were not corrected for log-transform bias, but predict only 13 tons/km^2/yr from watersheds with peak elevation 500-1,000 m (highest point of ~~UPPER~~Upper Faga'alu subwatershed is 653 m), and 68 tons/km^2/yr for max elevations of 1,000-3,000~~.~~ (Table 8). Given the high vegetation cover and lack of human ~~activity~~disturbance in the ~~UPPER Faga'alu~~Upper subwatershed, ~~its~~ sSSY ~~should~~is expected to be lower than ~~sSSY from~~ watersheds presented in Milliman and Syvitski (1992), ~~which included watersheds with human disturbance.~~but sSSY (uncorrected for log-transform bias) from the forested ~~UPPER~~Upper Faga'alu subwatershed (45-68 tons/km^2/yr) was approximately three to five times higher than the prediction from the Milliman and Syvitski (1992) model (13 tons/km^2/yr~~), though the~~). There is large scatter around their model ~~is large~~ for smaller watersheds, and the Faga’alu data fall within the range of scatter (Figures 5e and 6e in Milliman and Syvitski (1992)). Faga’alu is also a much smaller watershed and the study period was relatively short (3 years) compared to others included in their models.

~~Sediment yield has been~~SSY was measured ~~using modern fluvial measurements similar to ours for~~from two Hawaiian watersheds~~:~~ which are physiographically similar though much larger than Faga’alu~~,~~: Hanalei watershed on Kauai (“Hanalei~~”),~~”, 54 km^2), and Kawela watershed on Molokai (“Kawela~~”)~~”, 14 km^2) (Table 8) (Ferrier et al., 2013; Stock and Tribble, 2010). ~~Hanalei (54 km^2) has steep relief and mean areal precipitation of 3,866 mm~~Hanalei had slightly higher rainfall (3,866 mm/yr) than Faga’alu (3,247 mm/yr) but slightly lower SSC (mean 63 mg/L, maximum of 2,750 mg/L) than the Total Faga’alu watershed (mean 148 mg/L, maximum 3,500 mg/L) (Ferrier et al., 2013; Stock and Tribble, 2010). Kawela is drier than Faga’alu (P varies with elevation from 500-3,000 mm) and had much higher SSC (mean 3,490 mg/L, maximum 54,000 mg/L) than the Total Faga’alu watershed. SSY from Hanalei was 369 ± 114 tons/km^2/yr (Ferrier et al., 2013), which is ~~slightly higher than rainfall at Faga’alu during the monitoring period (3,247 mm/yr). Over a four year period, SSC at Hanalei averaged 63 mg/L and reached a maximum of 2,750 mg/L (Stock and Tribble, 2010), which is slightly lower than observations at the outlet of Faga’alu (mean 148 mg/L, maximum 3,500 mg/L). Calhoun and Fletcher (1999) estimated sSSY from Hanalei as 140±55 tons/km^2/yr, but had fewer data than Stock and Tribble (2010), who estimated sSSY as 525 tons/km^2/yr. Ferrier et al., (2013) reported annual suspended sediment yield at Hanalei as 369 ± 114 tons/km^2/yr. These values are higher than observed from the undisturbed subwatershed in Faga’alu (45-68 tons/km^2/yr) but similar to the disturbed (430-441 tons/km^2/yr) subwatersheds. Rocks at Hanalei are of similar age (1.5 Mya) or older (3.95-4.43 Mya) (Ferrier et al., 2013) compared with Faga’alu (1.2 Mya) (McDougall, 1985), so landscape age does not explain the difference in observed SSY between Hanalei and Faga’alu. Kawela (14 km^2) is disturbed by grazing and is in a sub-humid climate, where precipitation varies with elevation from 500-3,000 mm. Stock and Tribble (2010)~~higher than the undisturbed subwatershed in Faga'alu (45-143 tons/km^2/yr) but similar to the disturbed Lower (441-598 tons/km^2/yr) subwatersheds. Stock and Tribble (2010) estimated ~~sSSY~~SSY from Kawela was 459 tons/km^2/yr, ~~which is~~ similar to the disturbed ~~subwatershed in Faga'alu, but nearly twice as high as the TOTAL~~Lower Faga'alu watershed~~. In Kawela, SSC (mean 3,490 mg/L, maximum 54,000 mg/L) was much~~, but higher than ~~measured in Faga'alu TOTAL watershed, so the difference in SSY is due in part to higher SSC rather than to higher observed runoff.~~the Total Faga'alu watershed (241-368 tons/km^2/yr). Overall, both Hawaiian watersheds have higher SSY than Faga'alu, which is consistent with the low Qmax-SSY_{EV} intercepts ~~of Faga'alu in the Qmax-SSY_{EV} relationships,~~ and suggests ~~that~~ Faga'alu ~~may have uniquely~~has relatively low erosion rates for a steep, volcanic watershed. Precipitation variability may contribute to the difference in SSY, so a more thorough comparison between Hanalei and Faga'alu would require a storm-wise analysis of the type performed here.

<Table 8 here please>

~~Annual sSSY from the quarry was estimated from Equation 6 to be approximately 2,800 tons/km²/yr. The quarry surfaces are comprised of haul roads, piles of overburden, and steep rock faces which can be described as a mix of unpaved roads and cut-slopes. sSSY from cutslopes varies from 0.01 tons/km²/yr in Idaho (Megahan, 1980) to 105,000 tons/km²/yr in Papua New Guinea (Blong and Humphreys, 1982), so the sSSY ranges measured in this study are well within the ranges found in the literature.~~

~~5.4 Comparison with other kinds of sediment disturbance~~

~~SSY at Faga'alu was increased by 3.9x compared with the natural background. Other studies in small, mountainous watersheds have documented one to several orders of magnitude increases in SSY from land use that disturbs a small fraction of the watershed area. Urbanization~~

~~and mining can increase sediment yield by two to three orders of magnitudes in catchments of several km^2. Yields from construction sites can exceed those from the most unstable, tectonically active natural environments of Southeast Asia (Douglas, 1996). In Kawela watershed on Molokai, less than 5% of the land produces most of the sediment, and only 1% produces ~50% of the sediment (Risk, 2014; Stock et al., 2010). In three basins on St. John, US Virgin Islands unpaved roads increased sediment delivery rates by 3-9 times (Ramos-Scharrón and Macdonald, 2005).~~

~~Disturbances at larger scales have resulted in increases in total SSY to coral environments, similar to Faga'alu. The development of the Great Barrier Reef (GBR) catchment (423,000 km^2) since European settlement (ca.1830) led to increases in SSY by an estimated factor of 5.5x (Kroon et al., 2012). Mining has been a major contributor of sediment in other watersheds on volcanic islands with steep topography and high precipitation, increasing sediment yields by 5-10 times in a watershed in Papua New Guinea (Hettler et al., 1997; Thomas et al., 2003). In contrast to other land disturbances like fire, logging, or urbanization where sediment disturbance decreases over time, the disturbance from mining is persistently high. Disturbance magnitudes are similar to the construction phase of urbanization (Wolman and Schick, 1967), or high-traffic unpaved roads (Reid and Dunne, 1984), but persist or even increase over time.~~

~~While unpaved roads are often identified as a source of sediment in humid forested regions (Lewis et al., 2001; Ramos-Scharrón and Macdonald, 2005; Reid and Dunne, 1984), field observations at Faga'alu suggested that most roads in the urban area were stabilized with aggregate and not generating significant amounts of sediment. Other disturbances in Faga'alu included a few small agricultural plots, small construction sites and bare dirt on roadsides. Repeated surface disturbance at the quarry is a key process maintaining high rates of sediment~~

~~generation. Given the large distance to other sources of building material, aggregate mining and associated sediment disturbance may be a critical sediment source on remote islands in the Pacific and elsewhere.~~

6. Conclusion

Human disturbance has increased sediment yield to Faga'alu Bay by 3.9x over pre-disturbance levels. The human-disturbed subwatershed accounted for the majority (87%) of ~~total~~Total sediment yield, and the quarry (1.1% of watershed area) contributed about a third of ~~total~~Total SSY to the Bay. The anthropogenic impact on SSY_{EV} may vary by storm magnitude, as documented in Pacific Northwest forests (Lewis et al., 2001), but the storm metric models developed here showed contradictory results. Qmax was a good predictor of SSY_{EV} in both the disturbed and undisturbed watersheds, making it a promising predictor in diverse environments. The slopes of the Qmax-SSY_{EV} relationships were comparable with other studies, but the model intercepts were an order of magnitude lower than intercepts from watersheds in semi-arid to semi-humid climates. This suggests that sediment availability is relatively low in the Faga'alu watershed, either because of the heavy forest cover or volcanic rock type.

~~The event-wise approach did not require continuous in situ monitoring for a single or multiple years, which would not have been logistically possible in this remote study area.~~ This study presents an innovative method to combine sampling and analysis strategies to measure sediment contributions from key sources, estimate baseline annual sediment yields prior to management, and rapidly develop an empirical sediment yield model for a remote, data-poor watershed. While the instantaneous Q-SSC relationship illustrated large increases in SSC downstream of the quarry, the hysteresis and interstorm variability meant that a single Q-SSC relationship could not be used to estimate sediment loading, which is common in many

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watersheds (Asselman, 2000; Stock and Tribble, 2010). From a management perspective, the event-wise approach was useful for determining change over space and time without the problem of interannual variability in precipitation or the need for continuous, multi-year monitoring in a remote area. This approach is less expensive than efforts to measure annual yields and can be rapidly conducted if mitigation or disturbance activities are already planned.

Acknowledgements

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Funding for this project was provided by NOAA Coral Reef Conservation Program (CRCP) through the American Samoa Coral Reef Advisory Group (CRAG). Kristine Bucchianeri at CRAG and Susie Holst at NOAA CRCP provided ~~necessary and~~ significant support. Christianera Tuitele, Phil Wiles, and Tim Bodell at American Samoa Environmental Protection Agency (ASEPA), and Fatima Sauafea-Leau and Hideyo Hattori at NOAA, provided on-island coordination with traditional local authorities. Dr. Mike Favazza provided critical logistical assistance in American Samoa. Robert Koch at the American Samoa Coastal Zone Management Program (ASCMP) and Travis Bock at ASEPA assisted in accessing historical geospatial and water quality data. ~~Many others helped and supported the field and laboratory work including~~ Professor Jameson Newtson, Rocco Tinitali, and Valentine Vaeoso at American Samoa Community College (ASCC), Meagan Curtis and Domingo Ochavillo at American Samoa Department of Marine and Wildlife Resources (DMWR), Don and Agnes Vargo at American Samoa Land Grant, Christina Hammock at NOAA American Samoa Climate Observatory, and Greg McCormick at San Diego State University~~.~~ supported the field and laboratory work. George Poysky, Jr., George Poysky III, and Mitch Shimisaki at Samoa

Maritime Ltd. provided unrestricted access to the Faga'alu quarry ~~site~~, and historical operation information. Faafetai tele lava.

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TITLE:

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

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ABSTRACT

Suspended sediment concentrations (SSC) and yields (SSY) during storm and non-storm periods, 2012-2014, were measured from undisturbed and human-disturbed portions of a small (1.8 km^2), mountainous watershed that drains to a sediment-stressed coral reef. Event-wise SSY (SSY_{EV}) was calculated for 142 storms from measurements of water discharge (Q), turbidity (T), and SSC measured downstream of three key sediment sources: undisturbed forest, an aggregate quarry, and a village. SSC and SSY_{EV} were significantly higher downstream of the quarry during both storm- and non-storm periods. The human-disturbed subwatershed (10.1% disturbed) accounted for an average of 87% of SSY_{EV} from the watershed. Observed sediment yield (mass) to the coast, including human disturbed subwatersheds, was 3.9x the natural background. Specific SSY (mass/area) from the disturbed quarry area was 49x higher than from natural forest compared with 8x higher from the village area. Similar to mountainous watersheds in semi-arid and temperate climates, SSY_{EV} from both the undisturbed and disturbed watersheds correlated closely with maximum event discharge (Qmax), event total precipitation and event total Q, but not with the Erosivity Index. Best estimates of annual SSY varied by method, from 45-143

tons/km^2/yr from the undisturbed subwatershed, 441-598 tons/km^2/yr from the human-disturbed subwatershed, and 241-368 tons/km^2/yr from the total watershed. Sediment yield was very sensitive to disturbance; the quarry covers 1.1% of the total watershed area, but contributed 36% of SSY_{EV}. Given the limited access to gravel for infrastructure development, sediment disturbance from local aggregate mining may be a critical sediment source on remote islands in the Pacific and elsewhere. Identification of erosion hotspots like the quarry using rapid, event-wise measures of suspended sediment yield will help efforts to mitigate sediment stress and restore coral reefs.

Keywords:

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

1. Introduction

Human disturbances including deforestation, agriculture, roads, mining, and urbanization alter the timing, composition, and amount of sediment loads to downstream ecosystems (Syvitski et al., 2005). Increased sediment yields can stress aquatic ecosystems downstream of impacted watersheds, including coral reefs, by decreasing light for photosynthesis and increasing sediment accumulation rates (Fabricius, 2005; Storlazzi et al., 2015). Anthropogenic sediment disturbance can be particularly high on volcanic islands in the humid tropics, where erosion potential is high due to high rainfall and steep slopes (Milliman and Syvitski, 1992). The steep topography and small floodplains on small volcanic islands limits sediment storage and the buffering capacity of the watershed against increased hillslope sediment supply (Walling, 1999). Such environments characterize many volcanic islands in the South Pacific and elsewhere where many coral reefs are sediment-stressed (Bégin et al., 2014; Fallon et al., 2002; Hettler et al., 1997; Rotmann and Thomas, 2012).

A large proportion of sediment yield can originate from disturbances that cover small fractions of the watershed area, suggesting management should focus on erosion hotspots. In the grazing-disturbed Kawela watershed on Molokai, Hawaii, most of the sediment originated from less than 5% of the watershed area, and 50% of the sediment originated from only 1% of the watershed (Risk, 2014; Stock et al., 2010). On St. John in the Caribbean, unpaved roads covering 0.3-0.9% of the watershed were the dominant sediment source, and increased sediment yield to the coast by 5-9x relative to undisturbed watersheds (Ramos-Scharrón and Macdonald, 2007). In the U.S. Pacific Northwest, most road-generated sediment originated from just a small fraction of unpaved roads (Gomi et al., 2005; Henderson and Toews, 2001; Megahan et al., 2001; Wemple et al., 1996), and heavily used roads yielded 130x as much sediment as abandoned roads (Reid and Dunne, 1984).

Sediment management requires linking changes in land use to changes in sediment yields at the watershed outlet (Walling and Collins, 2008). A sediment budget quantifies sediment movement from key sources like hillslope erosion, channel-bank erosion, and mass movements, to its eventual exit from a watershed (Rapp, 1960). Walling (1999) used a sediment budget to show that sediment yield from watersheds can be insensitive to land use change and erosion management due to high sediment storage capacity on hillslopes and in the channel. Sediment yield from disturbed areas can also be large but relatively unimportant compared to high yields from undisturbed areas. The sediment budget can be simplified since most applications require only the order of magnitude or relative importance of processes be known (Slaymaker, 2003). Reid and Dunne (1996) argue a management-focused sediment budget can be developed quickly where the problem is clearly defined and the management area can be divided into homogenous sub-units.

Knowledge of suspended sediment yield (SSY) under both natural and disturbed conditions on most tropical, volcanic islands remains limited, due to the challenges of in situ monitoring in remote environments. Existing erosion models are mainly designed for agricultural landscapes, which are not well-calibrated to the physical geography of steep, tropical islands, and ignore important processes like mass movements (Calhoun and Fletcher, 1999; Ramos-Scharrón and Macdonald, 2005; Sadeghi et al., 2007). Models that predict SSY from small, mountainous catchments would establish baselines for change-detection, and improve regional-scale sediment yield models (Duvert et al., 2012).

Traditional approaches to quantifying human impact on sediment budgets include comparison of total annual yields (Fahey et al., 2003) and sediment rating curves (Asselman, 2000; Walling, 1977). These approaches are complicated by interannual climatic variability and hysteresis in the discharge-sediment concentration relationship (Ferguson et al., 1991; Gray et al., 2014; Kostaschuk et al., 2002; Stock and Tribble, 2010). Sediment yield can be highly variable over various time scales, even under natural conditions. At geologic time scales, sediment yield from a disturbed watershed may decrease as it reaches steady-state, or sediment contributions from subwatersheds may change with time (Ferrier et al., 2013; Perroy et al., 2012). At decadal scales, cyclical climatic patterns like El Nino-Southern Oscillation events or Pacific Decadal Oscillation can significantly alter sediment yield from undisturbed watersheds (Wulf et al., 2012).

SSY generated by storm events of the same magnitude can be used to compare the contribution of subwatersheds to total SSY (Zimmermann et al., 2012), determine temporal changes in SSY (Bonta, 2000), and relate SSY to various precipitation or discharge variables ("storm metrics") (Basher et al., 2011; Duvert et al., 2012; Fahey et al., 2003; Hicks, 1990). The relative anthropogenic impact on SSY_{EV} may vary by storm magnitude, as documented in Pacific Northwest forests (Lewis et al., 2001). As storm magnitude increases, water yield and/or SSY_{EV} from natural areas may increase relative to human-disturbed areas, diminishing anthropogenic impact relative to the natural baseline. While large storms account for most SSY under undisturbed conditions, the disturbance ratio (DR) may be highest for small storms, when background SSY_{EV} from the undisturbed forest is low and erodible sediment from disturbed surfaces is the dominant source (Lewis et al., 2001). For large storms, mass movements and bank erosion in undisturbed areas can increase the natural background and reduce the DR for large events.

Event-wise SSY (SSY_{EV}) may correlate with storm metrics such as total precipitation, the Erosivity Index (EI) (Kinnell, 2013), or total discharge, but the best correlation has consistently been found with maximum event discharge (Qmax). The EI quantifies the erosive energy of rainfall. Several researchers have hypothesized that Qmax integrates the hydrological response of a watershed, making it a good predictor of SSY_{EV} in diverse environments (Duvert et al., 2012; Rankl, 2004). High correlation between SSY_{EV} and Qmax has been found in semi-arid, temperate, and sub-humid watersheds in Wyoming (Rankl, 2004), Mexico, Italy, France (Duvert et al., 2012), and New Zealand (Basher et al., 2011; Hicks, 1990), but this approach has not been attempted for steep, tropical watersheds on volcanic islands.

This study uses in situ measurements of precipitation (P), water discharge (Q), turbidity (T) and suspended sediment concentration (SSC) to accomplish three objectives and answer the following research questions:

1) Quantify suspended sediment concentrations (SSC) and yields (SSY) at the outlets of undisturbed and human-disturbed portions of Faga'alu watershed during storm and non-storm periods. How does SSC vary between storm and non-storm periods? How much has human disturbance increased SSY during storm events? Which land uses dominate the anthropogenic contribution to SSY?
2) Develop an empirical model to predict SSY_{EV} from easily-monitored discharge or precipitation metrics. Which storm metric is the best predictor of SSY_{EV}? How does human-disturbance to SSY vary with storm metric?
3) Estimate annual SSY using the measurements from Objective 1, and modeling results from Objective 2. How does SSY at the field site compare to other volcanic tropical islands and other disturbed watersheds?

2. Study Area

Faga'alu (Fong-uh ah-loo) watershed is located on Tutuila (14S, 170W), American Samoa, which is comprised of steep, heavily forested mountains with villages and roads mostly confined to the flat, coastal areas. The coral reef in Faga'alu Bay is highly degraded by sediment (Fenner et al., 2008) and Faga'alu watershed was selected by the US Coral Reef Task Force (USCRTF) as a Priority Watershed for conservation and remediation efforts (Holst-Rice et al., 2015).

The administrative boundary of Faga'alu includes the watersheds of the main stream (1.78 km^2) and several small ephemeral streams that drain directly to the bay (0.63 km^2) (grey dotted boundary in Figure 1, "Admin."). Faga'alu watershed is drained by the main stream, which runs ~3 km from Matafao Mountain to Faga'alu Bay (area draining to FG3 in Figure 1, “Total” watershed). The Total watershed can be divided into an undisturbed, Upper watershed (area draining to FG1, “Upper”), and a human-disturbed, Lower watershed (area draining to FG3, “Lower”). The Lower watershed can be further subdivided to isolate the impacts of an aggregate quarry (area draining between FG1 and FG2, “Lower_Quarry”) and urbanized village area (area draining between FG2 and FG3, “Lower_Village”) (Figure 1).

<Figure 1 here please>

Faga’alu occurs on intracaldera Pago Volcanics formed about 1.20 Mya (McDougall, 1985). Soil types in the steep uplands are rock outcrops (15% of the watershed area) and well-drained Lithic Hapludolls ranging from silty clay to clay loams 20-150 cm deep (Nakamura, 1984). Soils in the lowlands include a mix of deep (>150 cm), well drained very stony silty clay loams, and poorly drained silty clay to fine sandy loam along valley bottoms. The mean slope of Faga'alu watershed is 0.53 m/m and total relief is 653 m.

2.1 Climate

Annual precipitation (P) in Faga'alu watershed is 6,350 mm at Matafao Mtn. (653 m m.a.s.l), 5,280 mm at Matafao Reservoir (249 m m.a.s.l.) and ~3,800 mm on the coastal plain (Craig, 2009; Dames & Moore, 1981; Perreault, 2010; Tonkin & Taylor International Ltd., 1989; Wong, 1996). There are two rainfall seasons: a drier winter from June through September accounts for 25% of annual P, and a wetter summer from October through May accounts for 75% of annual P (Craig, 2009; Perreault, 2010). P is lower in the drier season but large storms still occur: at 11 stream gages around the island, 35% of annual peak flows occurred during the drier season (1959-1990) (Wong, 1996).

2.2 Land Cover and Land Use

2.2.1 Vegetation, agriculture, and urban areas

The predominant land cover in Faga'alu watershed is undisturbed vegetation on the steep hillsides (95%), including forest (86%) and scrub/shrub (9%) (Table 1). The Upper watershed is dominated by undisturbed rainforest (82%) on steep hillslopes with no human disturbance. The Lower subwatershed has steep, vegetated hillslopes and a relatively small flat area in the valley bottom that is urbanized (6.4% "High Intensity Developed" in Table 1). A small portion of the watershed (1.8%) is developed open space, mainly landscaped lawns and parks. Agricultural areas include small household gardens and small areas of banana and taro on the steep hillsides, classified as grassland (0.3% GA, Table 1) due to high fractional grass cover. Most unpaved roads are stabilized with compacted gravel and do not appear to be a major sediment source (Horsley-Witten, 2012).

<Table 1 here please>

2.2.2 Aggregate quarry and reservoirs

An aggregate quarry covering 1.6 ha has been in continuous operation since the 1960's (Latinis et al., 1996) and accounted for nearly all of the bare land in Faga'alu watershed (1.1%) (Table 1). Sediment eroded from the quarry was discharged directly to Faga'alu stream until 2011, when quarry operators installed silt fences and small settling ponds (Horsley-Witten, 2011), which were inadequate to control the large amount of sediment mobilized during storms (Horsley-Witten, 2012). During the study period (2012-2014), additional sediment controls were installed and large piles of overburden were overgrown by vegetation (Figure 2). In late 2014, after the monitoring reported here, large retention ponds were installed to capture sediment runoff. See Holst-Rice et al. (2015) for description of sediment mitigation at the quarry.

<Figure 2 here please>

Three water impoundment structures were built in the early 1900's in the Upper watershed for drinking water supply and hydropower, but none are in use and the reservoir at FG1 is filled with coarse sediment. Other deep pools at the base of waterfalls in the upper watershed have no fine sediment and we assume the other reservoirs are not retaining fine suspended sediment. A full description of the reservoirs is in Supplementary Material A.

3. Methods

The field methods used to calculate event-wise suspended sediment yield (SSY_{EV}) are described in section 3.1. The equations and analytical methods used to accomplish Objectives 1-3 are described in sections 3.2-3.4. Briefly, the in-stream suspended sediment yield (SSY, tons) and specific suspended sediment yield (sSSY, tons/km^2) (*sensu* Walling and Webb (1996)) were calculated for individual storm events (SSY_{EV}, $sSSY_{EV}$) at three locations in Faga'alu watershed using calculated discharge (Q) and suspended sediment concentration (SSC)(Figure 1) (Section 3.1). Q was calculated from continuously recorded stage and a stage-discharge relationship calibrated with field measurements (Section 3.1.2). SSC was measured directly from grab samples or modeled from continuously monitored turbidity (T) and T-SSC relationships calibrated to in-stream SSC (Section 3.1.3). Storm events were identified using automated hydrograph separation, and SSY_{EV} calculated for each monitored location with the Q and SSC data (Section 3.2.1). The subwatersheds were nested, so SSY_{EV} contributions from subwatersheds were calculated by subtracting SSY_{EV} at the upstream subwatershed from SSY_{EV} at the given downstream subwatershed. SSY from disturbed surfaces was calculated assuming a spatially uniform SSY from forested parts of disturbed subwatersheds (Section 3.2.2). The cumulative probable error (PE) of SSY_{EV} was calculated for each storm to incorporate errors in Q and SSC, and different T-SSC relationships were tested for their impact on SSY estimates (Section 3.2.3). Log-linear regression models were developed to predict SSY_{EV} from storm metrics for the undisturbed and disturbed subwatersheds (Section 3.3). Annual SSY was estimated from the regression models and the ratio of annual storm precipitation to the precipitation during storms where SSY_{EV} was measured (Section 3.4).

Measurements of SSY at FG1, FG2 and FG3 quantify the in-stream suspended sediment budget. Other components of sediment budgets not measured in this study include channel erosion, channel deposition, and floodplain deposition (Walling and Collins, 2008). In Faga'alu, the channel bed is predominantly large volcanic cobbles and gravel, with no significant deposits of fine sediment. Upstream of the village, the valley is very narrow with no floodplain. In the Lower watershed the channel has been stabilized with cobble reinforced by fencing, so overbank flows and sediment deposition on the floodplain are not observed. We therefore assume that channel erosion and channel and floodplain deposition are insignificant components of the sediment budget, and the measured sediment yields at the three locations reflect differences in hillslope sediment supply.

3.1 Field Data Collection

Data on P, Q, SSC, and T were collected during four field campaigns: January-March 2012, February-July 2013, January-March 2014, and October-December 2014, and several intervening periods of unattended monitoring by instruments with data loggers. Field sampling campaigns were scheduled to coincide with the period of most frequent storms in the November-May wet season, though large storms were sampled throughout the year.

3.1.1 Precipitation (P)

P was measured in Faga'alu watershed from January, 2012, to December, 2014, using a tipping-bucket rain gage located at the quarry near the centroid of the watershed (RG1; 20cm dia., 1-minute resolution) and a Vantage Pro Weather Station located at the stream outlet to the ocean (Wx; 20cm dia. 15-minute resolution) (Figure 1). Data from a third rain gage, (RG2) was recorded from January to March, 2012 to determine an orographic precipitation relationship. Total event precipitation (Psum) was calculated using 1 min interval data from RG1, with data gaps filled by 15-minute interval precipitation data from Wx.

3.1.2 Water Discharge (Q)

Stream gaging sites were chosen to take advantage of an existing control structure (FG1) and a stabilized stream cross section (FG3). At FG1 and FG3, Q was calculated from stream stage recorded at 15-minute intervals using HOBO and Solinst pressure transducers (PT) and a stage-Q rating curve calibrated to Q measurements. Q was measured manually in the field over a range of flow conditions by the area-velocity method (AV) using a Marsh-McBirney flowmeter (Harrelson et al., 1994; Turnipseed and Sauer, 2010). Q measurements were not made at the highest stages recorded by the PTs, so the stage-Q rating curve at FG3 was extrapolated using Manning's equation, calibrating Manning's n (0.067) to the Q measurements. At FG1, the flow control structure is a masonry spillway crest, so the HEC-RAS model was used to create the stage-Q relationship and calibrated to Q measurements (Brunner, 2010). See Supplementary Material B for further details on stream gaging at FG1 and FG3.

A suitable site for stream gaging was not present at the outlet of the Lower_Quarry subwatershed (FG2), so water discharge at FG2 was calculated as the product of the specific water discharge from FG1 (m^3/km^2) and the watershed area draining to FG2 (1.17 km^2). The specific water discharge at FG2 is assumed to be the same as above FG1 since average slopes, vegetation, and soils of the watersheds are extremely similar. Discharge may be higher from the quarry surface, which represents 5.7% of the Lower_Quarry subwatershed, so Q and SSY at FG2 are conservative, lower-bound estimates, particularly during small events when specific discharge from the Upper watershed was small relative to specific discharge from the quarry. The quarry surface is continually being disturbed, sometimes with large pits excavated and refilled in the course of weeks, as well as intentional water control structures implemented over time. Given the changes in the contributing area of the quarry, estimates of water yield from the quarry were uncertain, so we assumed a uniform specific discharge for the whole Lower_Quarry subwatershed.

3.1.3 Suspended Sediment Concentration (SSC)

SSC was estimated at 15 minute intervals from either 1) linear interpolation of stream water samples, or 2) turbidity data (T) recorded at 15 minute intervals and a T-SSC relationship calibrated to stream water samples. Stream water was collected by grab sampling with 500 mL HDPE bottles at FG1, FG2, and FG3. At FG2, water samples were also collected at 30 minute intervals during storm events by an ISCO 3700 Autosampler triggered by a water level sensor. The Autosampler inlet tubing was oriented down-stream, just below the water level sensor, approximately 30 cm above the stream bed, on rebar positioned midstream. Samples were analyzed for SSC on-island using gravimetric methods (Gray, 2014; Gray et al., 2000). Water samples were vacuum filtered on pre-weighed 47mm diameter, 0.7 µm Millipore AP40 glass fiber filters, oven dried at 100 C for one hour, cooled and weighed to determine SSC (mg/L).

Interpolation of SSC from grab samples was performed if at least three samples were collected during a storm (Nearing et al., 2007), and if an SSC sample was collected within 30 minutes of peak Q. Based on low observed SSC between storm events, SSC was assumed to be zero at the beginning and end of each storm if no sample was available for those times (Lewis et al., 2001).

T was measured at FG1 and FG3 using three types of turbidimeters: 1) Greenspan TS3000 (TS), 2) YSI 600OMS with 6136 turbidity probe (YSI), and 3) two Campbell Scientific OBS500s (OBS). All turbidimeters were permanently installed in PVC housings near the streambed with the turbidity probe submerged at all flows and oriented downstream. Despite regular maintenance, debris fouling and vandalism caused frequent data loss.

A unique, linear T-SSC relationship was developed for the YSI and both OBS turbidimeters at each location using linear regression on T data and SSC samples from storm periods (r^2 values 0.79-0.99, Supplementary Material C). The T-SSC relationship can be unique to each region, stream, instrument or even each storm event (Lewis et al., 2001), and can be influenced by water color, dissolved solids, organic matter, temperature, and particle shape, size, and composition. Despite the multiple factors relating T to SSC, T is a robust predictor of SSC in streams (Gippel, 1995), and is most accurate when a unique T-SSC relationship is developed for each instrument and field site separately, using in situ SSC samples during storms (Lewis, 1996; Minella et al., 2008). The TS meter at FG1 was vandalized before sufficient samples had been collected to establish a T-SSC relationship for high T data, so the T-SSC relationship from the YSI was used for the TS data. Errors were higher at FG3 (RMSE 112% for YSI, 46% for OBS), and lower at FG1 (RMSE 13% for YSI at FG1). The T-SSC relationship for the YSI predicted higher SSC at FG3 than at FG1 for the same T value (Supplementary Material C), which introduces uncertainty in SSC and SSY at FG3. The impact of using the same T-SSC relationship at both FG1 and FG3 is tested in the error analysis (Section 3.2.3). The critical assumption in our application is that the parameters of the T-SSC relationship are stable over time and among storm events. The T-SSC relationships are critical to SSY calculations, so the cumulative error from these relationships were combined with other error sources to estimate uncertainty in the SSY_{EV} estimates (Section 3.2.3). See Supplementary Material C for further details on T-SSC relationships at FG1 and FG3

3.2 SSY_{EV} for disturbed and undisturbed watersheds

3.2.1 Suspended Sediment Yield during storm events (SSY_{EV})

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

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

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^{-9}).

Storm events can be defined by P (Hicks, 1990) or Q data (Duvert et al., 2012), and the method used to identify storm events can significantly influence the analysis of SSY_{EV} (Gellis, 2013). Due to the large number of storm events and the prevalence of complex storm events observed at the study site, we used a digital filter signal processing technique (Nathan and McMahon, 1990) in the R-statistical package EcoHydRology (Fuka et al., 2014), which separates the hydrograph into quickflow, or direct surface or subsurface runoff that occurs during storms, and baseflow or delayed flow (Hewlett and Hibbert, 1967). Quickflow and baseflow components are not well defined in terms of hydrologic flow path; here we use the separation operationally to define storm events. Spurious events were sometimes identified due to instrument noise, so only events with quickflow lasting at least one hour and peak quickflow greater than 10% of baseflow were included (See Supplementary Material D for example).

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

3.2.2 SSY from disturbed and undisturbed portions of subwatersheds

Land cover in the Lower subwatersheds (Lower_Quarry and Lower_Village) includes both undisturbed forest and human-disturbed surfaces (Table 1). SSY_{EV} from disturbed areas only was estimated as:

$$SSY_{EV\_distrb} = SSY_{EV\_subws} - (sSSY_{EV\_UPPER} * Area_{undist}) \qquad \text{Equation 2}$$

where SSY_{EV_distrb} is SSY_{EV} from disturbed areas only (tons), SSY_{EV_subws} is SSY_{EV} (tons) measured from the subwatershed, $sSSY_{EV\_UPPER}$ is specific SSY_{EV} ($tons/km^2$) from the Upper subwatershed (SSY_{EV_FG1}), and $Area_{undist}$ is the area of undisturbed forest in the subwatershed (km^2). This calculation assumes that forests in all subwatersheds have SSY similar to the Upper watershed.

The disturbance ratio (DR) is the ratio of SSY_{EV} under current conditions to SSY_{EV} under pre-disturbance conditions:

$$\mathrm{DR} = \frac{SSY_{EV\_subw}}{A_{subw} * \ sSSY_{EV\_UPPER}} \qquad \text{Equation 3}$$

where A_{subw} is the area of the subwatershed. Both Equations 2 and 3 assume that $\mathrm{sSSY_{EV}}$ from forested areas in the Lower subwatershed equals $\mathrm{sSSY_{EV}}$ from the undisturbed Upper watershed and that pre-disturbance land cover was forested throughout the watershed.

3.2.3 Error Analysis

Uncertainty in $\mathrm{SSY_{EV}}$ calculations arises from errors in measured and modeled Q and SSC (Harmel et al., 2006). The root mean square error propagation method estimates the "most probable value" of the cumulative or combined error by propagating the error from each measurement and modeling procedure, i.e. stage-Q and T-SSC, to the final $\mathrm{SSY_{EV}}$ calculation (Topping, 1972). The resulting cumulative probable error (PE) is the square root of the sum of the squares of the maximum values of the separate errors:

$$PE = \sqrt{(E_{Qmeas}^2 + E_{SSCmeas}^2) + (E_{Qmod}^2 + E_{SSCmod}^2)} \qquad \text{Equation 4}$$

where *PE* is the cumulative probable error for $\mathrm{SSY_{EV}}$ estimates (±%), E_{Qmeas} is uncertainty in Q measurements (±%), $E_{SSCmeas}$ is uncertainty in SSC measurements (± %), E_{Qmod} is uncertainty in the Stage-Q relationship (RMSE, as ±% of the mean observed Q), E_{SSCmod} is uncertainty in the T-SSC relationship or from interpolating SSC samples (RMSE, as ± % of the mean observed SSC) (Harmel et al., 2009).$\mathrm{E_{Qmeas}}$ and $\mathrm{E_{SSCmeas}}$ were taken from the DUET-H/WQ software tool lookup tables (Harmel et al., 2009).

The effect of uncertain $\mathrm{SSY_{EV}}$ estimates may complicate conclusions about anthropogenic impacts and storm metric-$\mathrm{SSY_{EV}}$ relationships, but difference in $\mathrm{SSY_{EV}}$ from undisturbed and disturbed areas was expected to be much larger than the cumulative uncertainty.

High uncertainty is common in sediment yield studies where successful models estimate SSY with ±50-100% accuracy (Calhoun and Fletcher, 1999; Duvert et al., 2012). PE was calculated for SSY_{EV} from the Upper and Total watersheds, but not for the Lower subwatershed since it was calculated as the difference of SSY_{EV_UPPER} and SSY_{EV_TOTAL}.

In addition to the error due to scatter about a given T-SSC relationship, there may also be uncertainty about the regression line itself, particularly where a given instrument shows different T-SSC relationships at different locations (Supplementary Material C). In Faga'alu, the T-SSC relationship estimated higher SSC for a given T value at the disturbed site (FG3) than the forested site (FG1). In order to test for the impact of using the same T-SSC relationship at both locations, we recalculated SSY_{EV} and the disturbance ratio using the T-SSC relationship at FG3 to estimate SSC at both FG3 and FG1.

3.3 Modeling SSY_{EV} with storm metrics

The relationship between SSY_{EV} and storm metrics was modelled as a log-linear function:

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

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

Four storm metrics were tested as predictors of SSY_{EV}: Total event precipitation (Psum), event Erosivity Index (EI) (Hicks, 1990; Kinnell, 2013), total event water discharge (Qsum), and maximum event water discharge (Qmax) (Duvert et al., 2012; Rodrigues et al., 2013). The Erosivity Index describes the erosive power of rainfall and was calculated for each storm event identified in Section 3.2.1 following the methodology of Kinnell (2013) using only 1 min interval data at RG1. The discharge metrics (Qsum and Qmax) were normalized by watershed area to compare different sized subwatersheds.

Model fits for each storm metric were compared using coefficients of determination (r^2) and Root Mean Square Error (RMSE). The correlation between storm metrics (X) and SSY_{EV} were quantified using non-parametric (Spearman) correlation coefficients. The regression coefficients (α and β) for the Upper and Total watersheds were tested for statistically significant differences using Analysis of Covariance (ANCOVA) (Lewis et al., 2001).

3.4. Estimation of annual SSY

Annual SSY (mass) and sSSY (mass/area) were estimated using 1) the developed storm metric-SSY_{EV} models, and 2) the ratio of annual storm precipitation to precipitation measured during storms with SSY_{EV} data.

An annual SSY time-series was not possible due to the discontinuous field campaigns and failure of or damage to the turbidimeters. Continuous records of P and Q were available for 2014, so the log-linear storm metric-SSY_{EV} models (Equation 5), including log-bias correction (Duan, 2016; Ferguson, 1986), were used to predict SSY_{EV} for all storms in 2014 (Basher et al., 1997). For storms missing Qmax data at FG3, Qmax was predicted from a linear regression between Qmax at FG1 and Qmax at FG3 for the study period (R^2 =0.88).

Annual SSY and sSSY were also estimated by multiplying SSY_{EV} from measured storms by the ratio of annual storm precipitation (P_{EVann}) to precipitation during storms where SSY_{EV} was measured (P_{EVmeas}):

$$SSY_{ann} = SSY_{EV\_meas} * \frac{P_{EVann}}{P_{EVmeas}} \qquad \text{Equation 6}$$

where SSY_{ann} is estimated annual SSY from storms, SSY_{EV_meas} is SSY_{EV} from sampled storms (all, Tables 2 and 4), P_{EVann} is the precipitation during all storm events in a year, and P_{EVmeas} is precipitation during the set of sampled storms. Equation 6 assumes that the sediment yield per mm of storm precipitation is constant over the year, and insensitive to the size distribution of storms, though there is evidence that SSY_{EV} increases exponentially with storm size (Lewis et al., 2001; Rankl, 2004). Equation 6 also ignores sediment yield during non-storm periods, which is justified by the low SSC (typically under 20 mg/L) and Q (baseflow) observed between storms.

4. Results

4.1 Field Data Collection

4.1.1 Precipitation

At RG1, P was 3,502 mm, 3,529 mm, and 3,709 mm in 2012, 2013, and 2014, respectively, which averages 94% of long-term P (=3,800 mm) (PRISM data; Craig, 2009). Daily P at RG1 was similar to P at Wx (regression slope=0.95, r^2=0.87) and at RG2 (slope=0.75, r^2=0.85). Higher P was expected at higher elevation at RG2 so lower P at RG2 was assumed to be caused by measurement error, as the only available sampling location was a forest clearing with high surrounding canopy. P measured at higher elevations would be useful to determine the orographic effect, but for this analysis the absolute values of P in each subwatershed are not as important since P and the Erosivity Index are only used as predictive storm metrics. Given the near 1:1 relationship between daily P measured at RG1 and Wx, P was assumed to be homogenous over the Lower subwatershed.

4.1.2 Water Discharge (Q)

Q at FG1 and FG3 was characterized by low but perennial baseflow, punctuated by flashy hydrograph peaks (Figure 3). Storm events were generally smaller but more frequent in the October-April wet season compared to the May-September dry season, when the largest event in the three year monitoring period was observed (August 2014).

< Figure 3 here please>

4.1.3 Suspended Sediment Concentrations (SSC) during storm and non-storm periods

<Figure 4 here please>

An example of a storm event on 2/14/2014 (Figure 4) shows that SSC at FG2 was highest on the rising limb of the hydrograph, and that T and SSC at FG3 were always higher than at FG1. SSC was consistently lowest at FG1, highest downstream of the quarry (FG2), and intermediate downstream of the village (FG3), during both storm and non-storm periods (Figure 5a, 5b). Mean and maximum SSC of all stream water samples were lowest at FG1 (μ=28 mg/L, max=500 mg/L, n=59), highest at FG2 (μ=337 mg/L, max=12,600 mg/L, n=90), and intermediate at FG3 (μ=148 mg/L, max=3,500 mg/L, n=159). SSC data at FG1-3 were non-normal, so non-parametric significance tests were applied. SSC was significantly different among the three sites during non-storms and storms ($p<10^{-4}$). Pair-wise Mann-Whitney tests between FG1 and FG2 were significant ($p<10^{-4}$ for both storms and non-storms). FG2 and FG3 were significantly different for non-storm periods ($p<0.05$) but not for storms ($p>0.10$) due to the high variance.

<Figure 5 here please>

SSC varied by several orders of magnitude for a given Q at FG1-3 (Figure 6) due to significant hysteresis observed during storm periods (Figure 4). Maximum SSC at FG1 (500 mg/L) was sampled on 04/23/2013 at high Q (Q_{FG1}= 3,724 L/sec) (Figure 6a). Maximum SSC at FG2 (12,600 mg/L) and FG3 (3,500 mg/L) were sampled during the same storm (03/05/2012) when brief but intense P caused high SSC runoff from the quarry, but Q was low (Figure 6b-c). SSC was diluted downstream of the quarry by the addition of lower SSC runoff from the village and forest draining to FG3.

<Figure 6 here please>

4.2 SSY_{EV} for disturbed and undisturbed watersheds

A total of 210 storms were identified January, 2012, to December, 2014. A total of 169 storms had simultaneous Q data at FG1 and FG3 (Supplementary Material D, Table 1). SSC data were recorded during 112 (FG1) and 74 storms (FG3). Of those storms, 42 had simultaneous P, Q, and SSC data at FG1 and FG3. Of those storms, only 8 had simultaneous P, Q, and SSC data at FG2. Storm events ranged from 1 hour to 2 days, with mean duration of 13 hours.

4.2.1 Suspended sediment yield during storm events (SSY_{EV}) from Upper, Lower, and Total watersheds

For the 42 storms with P, Q, and SSC data at both FG1 and FG3, SSY_{EV_TOTAL} was 129±121 tons, with 17±7 tons from the Upper watershed and 112 tons from the Lower subwatershed (Table 2). The Upper and Lower subwatersheds are similar in size (0.90 km² and 0.88 km²) but SSY_{EV_LOWER} accounted for 87% of SSY_{EV} at the watershed outlet. The DR (Equation 4, $sSSY_{EV}\_Upper$ = 18.8 tons/km²) suggests $sSSY_{EV}$ has increased by 6.8x in the

Lower subwatershed, and 3.9x for the Total watershed compared with undisturbed forest in the Upper watershed.

<Table 2 here please>

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

In the Lower subwatershed, disturbed areas cover 10% of the surface but contributed 87% of SSY_{EV_LOWER}. In the Total watershed, disturbed areas cover only 5.2% of the surface but contributed 75% of SSY_{EV_TOTAL}. sSSY from disturbed areas in the Lower subwatershed was 1,095 tons/km², or 58x the sSSY of undisturbed forest (Table 3).

<Table 3 here please>

4.2.3 Suspended sediment yield during storm events (SSY_{EV}) from Lower_Quarry and Lower_Village watersheds

For the 8 storms with P, Q, and SSC data at FG1-3, sSSY from the Upper, Lower_Quarry, Lower_Village, and the Total watershed was 15, 61, 27, and 26 tons/km², respectively, with 29% of SSY_{EV} from the Upper subwatershed, 36% from the Lower_Quarry subwatershed, and 35% from the Lower_Village subwatershed. The storms in Table 4 may underrepresent the contributions of the quarry and village to SSY, since they show a lower DR for the Total watershed (1.7x SSY_{UPPER}) compared with the 42 storms in Table 2 (3.9x SSY_{UPPER}). sSSY increased by 4.1x in the Lower_Quarry subwatershed and 1.8x in the Lower_Village subwatershed compared with the undisturbed Upper watershed.

<Table 4 here please>

4.2.4 SSY from disturbed and undisturbed portions of *Lower_Quarry* and *Lower_Village watersheds*

Disturbed areas cover small fractions of the subwatersheds, yet contributed roughly 77% of SSY $_{EV\_LOWER\_QUARRY}$ (6.5% disturbed) and 51% of SSY $_{EV\_LOWER\_VILLAGE}$ (11.7% disturbed). Similarly, disturbed areas cover 5.2% of the Total watershed but contributed 75-45% of SSY $_{EV\_TOTAL}$ (Tables 3 and 5). sSSY from disturbed areas in the Upper (37 tons/km^2), Lower_Quarry (722 tons/km^2), and Lower_Village subwatersheds (116 tons/km^2) suggested that disturbed areas increase sSSY over forested conditions by 49x and 8x in the Lower_Quarry and Lower_Village subwatersheds, respectively. Human disturbance in the Lower_Village subwatershed increased SSY_{EV} above natural levels but the magnitude of disturbance was much lower than the quarry.

<Table 5 here please>

4.2.5 Error analysis

Cumulative Probable Errors (PE) in SSY_{EV}, calculated from measurement and model errors in Q and SSC data, were 40-56% (μ=52%) at FG1 and 36-118% (μ=94%) at FG3.

The measurement error for Q at FG1 and FG3 was 8%, including area-velocity measurements (6%), continuous Q measurement in a natural channel (6%), pressure transducer error (0.1%), and streambed condition (firm, stable bed=0%) (DUET-H/WQ look-up table (Harmel et al., 2006)). Model errors were 32% for the stage-Q rating curve using Manning's equation at FG3, and 22% using HEC-RAS at FG1.

The measurement error for SSC was 16 %, including interpolating over a 30 min interval (5%), sampling during stormflows (3%), and measuring SSC by filtration (3.9%) (DUET-H/WQ look-up table (Harmel et al., 2006)). Model errors of the T-SSC relationships were 13% (3 mg/L) for the YSI and TS turbidimeters at FG1, 112% (342 mg/L) for the YSI turbidimeter at FG3, and 47% (46 mg/L) for the OBS turbidimeter at FG3.

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

4.3 Modeling SSY_{EV} with storm metrics

4.3.1 Selecting the best predictor of SSY_{EV}

Qsum and Qmax were the best predictors of SSY_{EV} for the forested Upper watershed, and Qmax was the best predictors for the Total watershed (Figure 7, Table 6). SSY_{EV} is calculated from Q so it is expected that Qsum correlated closely with SSY_{EV} (Duvert et al., 2012; Rankl, 2004). Discharge metrics were highly correlated with SSY_{EV} in the Total watershed, suggesting they are good predictors in both disturbed and undisturbed watersheds. Most of the scatter in the Qmax-SSY_{EV} relationship is observed for small events, and Qmax correlated strongly with the largest SSY_{EV} values, when most of the annual SSY is generated (Figure 7a).

<Table 6 here please>

4.3.2. Effect of event size and watershed disturbance

In general, SSY_{EV_TOTAL} was higher than SSY_{EV_UPPER} for the full range of measured storms with the exception of a few events. The outlier events could be from measurement error or mass movements in the Upper watershed. The event with much higher SSYEV at FG1 (Figure 7d) did not have corresponding data for FG2 or FG3, to determine if this event was data error. The separation of multi-peak storm events, storm sequence, and antecedent conditions may also play a role. While strong seasonality is not observed in Faga'alu, low rainfall can persist for several weeks, perhaps altering water and sediment dynamics in subsequent storm events.

<Figure 7 here please>

A higher intercept (α) for the human-disturbed compared to the undisturbed watershed indicates higher SSY_{EV} for the same size storm event. A difference in slope (β) indicates the relative subwatershed contributions vary with storm size. All storm metric-SSY_{EV} model intercepts (α) were significantly different ($p<0.01$), but only the Qsum-SSY_{EV} model showed significantly different slopes (β, $p<0.01$) (Figure 7, Table 6). The relative sediment contribution from the human-disturbed watershed was hypothesized to diminish with increasing storm size, but the results from P and Q metrics were contradictory. The Qsum-SSY_{EV} model indicates a decrease in relative contribution from the disturbed Lower watershed, but the Psum- and Qmax-SSY_{EV} models show no change over increasing storm size (Figure 7). It was hypothesized that SSY_{EV} from undisturbed forest would become the dominant source for larger storms, but the DR remains high for large storms due to naturally low SSY_{EV} from forest areas in Faga'alu watershed. This suggests that disturbed areas were not supply limited for the range of sampled storms.

4.4 Estimation of annual SSY

Annual SSY estimates varied, depending on which storm metric or set of storms (all, Table 2, Table 4) was used. The Qmax models (with bias correction) and Equation 6 using all events gave different annual SSY estimates at both the Upper watershed (41-129 tons/yr) and the Total watershed (655-428 tons/yr). The Psum model resulted in much lower estimates due to higher scatter about the Psum-SSY_{EV} relationship for large events, even with bias correction, compared with the more robust Qmax-SSY_{EV} model (Table 7). The Qmax-SSY_{EV} model prediction is sensitive to the storm-size distribution, with significantly more SSY_{EV} for events with higher Qmax. Comparing annual SSY estimates from different methods, using different sets of storm sizes can therefore make it appear that there is much disagreement when in fact this variability arises mostly from the variation in storm size distribution.

<Table 7 here please>

Annual storm precipitation (P_{EVann}) in 2014 was 2,770 mm, representing 69% of total annual precipitation (3,709 mm). The remaining 31% of precipitation did not result in a rise in stream level sufficient to be classified as an event with the method used here. All storms with measured SSY_{EV_UPPER} from 2012-2014 included 3,457 mm of precipitation (P_{EVmeas}), or 125% of P_{EVann}, so estimated annual SSY_{UPPER} (Equation 6) was 41 tons/yr (45 tons/km²/yr). All storms with measured SSY_{EV_TOTAL} from 2012-2014 included 2,628 mm of precipitation, or 95% of expected annual storm precipitation so estimated annual SSY_{TOTAL} was 428 tons/yr (241 tons/km²/yr).

5. Discussion

5.1 SSC and SSYEV for disturbed and undisturbed watersheds

5.1.1 SSC for disturbed and undisturbed watersheds in Faga'alu

At FG1, SSC variability during storms was assumed to be caused by landslides or channel erosion (including previous landslides) (Figure 6a). Anecdotal and field observations reported unusually high SSC at FG1 during 2013, possibly from landsliding during previous large storms (G. Poysky, pers. comm.). At FG2 and FG3, additional variability in the Q-SSC relationship was caused by changing sediment availability from quarrying operations and construction in the village. High SSC values observed downstream of the quarry (FG2) during low Q were caused by two mechanisms: 1) P that generated high SSC runoff but did not result in storms identified on the hydrograph, and 2) washing fine sediment into the stream during quarry operations.

Given the close proximity of the quarry to the stream, SSC at FG2 was highly influenced by mining activity like rock extraction, crushing, and/or hauling operations. During 2012, a common practice for removing fine sediment from crushed aggregate was to rinse it with water pumped from the stream. In the absence of retention structures the fine sediment was discharged directly to Faga'alu stream, causing high SSC during non-storm periods with no P in the preceding 24 hours (solid symbols, Figure 6b-c). In 2013 and 2014, riverine discharge or rinsed sediment was discontinued, and sediment was piled on-site where severe erosion of these changing stockpiles caused high SSC only during storm events.

5.1.2 Compare SSY_{EV} with other kinds of sediment disturbance

SSY at Faga'alu was 3.9x higher than the natural background. Studies in similar watersheds have documented one to several orders of magnitude increases in SSY from land use that disturbs a small fraction of the watershed area (Stock et al., 2010). Urbanization (construction-phase) and mining can increase SSY by two to three orders of magnitude in catchments of several km^2, exceeding yields from the most unstable, tectonically active natural environments of Southeast Asia (Douglas, 1996). In three basins on St. John, US Virgin Islands unpaved roads increased sediment delivery rates by 3-9 times (Ramos-Scharrón and Macdonald, 2005). Disturbances at larger scales in other coral reef areas have been similar to Faga'alu, such as the Great Barrier Reef (GBR) catchment (423,000 km^2) where SSY increased by a factor of 5.5x since European settlement (Kroon et al., 2012). Mining has been a major contributor of sediment in other watersheds on volcanic islands with steep topography and high precipitation, increasing sediment yields by 5-10 times in a watershed in Papua New Guinea (Hettler et al., 1997; Thomas et al., 2003). In contrast to other land disturbances like fire, logging, or urbanization where sediment disturbance decreases over time, the disturbance from mining is persistently high. Disturbance magnitudes are similar to the construction phase of urbanization (Wolman and Schick, 1967), or high-traffic unpaved roads (Reid and Dunne, 1984), but persist or even increase over time.

While unpaved roads are often a major sediment source in humid forested regions (Lewis et al., 2001; Ramos-Scharrón and Macdonald, 2005; Reid and Dunne, 1984), most roads in the urban area in Faga'alu were stabilized with aggregate and not generating significant amounts of sediment. Other disturbances in Faga'alu included a few small agricultural plots, small construction sites and bare dirt on roadsides. Repeated surface disturbance at the quarry is a key process maintaining high rates of sediment generation.

Annual sSSY from the quarry was estimated from Equation 6 and sSSY from disturbed area in the Lower_Quarry (Table 5) to be approximately 6,700 tons/km²/yr. The quarry surfaces are comprised of haul roads, piles of overburden, and steep rock faces which can be described as a mix of unpaved roads and cut-slopes. sSSY from cutslopes varies from 0.01 tons/km²/yr in Idaho (Megahan, 1980) to 105,000 tons/km²/yr in Papua New Guinea (Blong and Humphreys, 1982), so the sSSY ranges measured in this study are well within the ranges found in the literature.

5.2 Modeling SSY_{EV} with storm metrics

Similar to other studies, the highest correlations with SSY_{EV} at Faga'alu were observed for discharge metrics Qsum and Qmax (Basher et al., 2011; Duvert et al., 2012; Fahey et al., 2003; Hicks, 1990; Rankl, 2004; Rodrigues et al., 2013). Given the high correlation coefficients between SSY_{EV} and Qmax in both watersheds, Qmax may be a promising predictor that integrates both precipitation and discharge processes in diverse watersheds.

In Faga'alu, SSY_{EV} was least correlated with the EI. Rodrigues et al. (2013) hypothesized that EI is poorly correlated with SSY_{EV} due to the effect of previous events on antecedent moisture conditions and in-channel sediment storage. Cox et al. (2006) found EI was more correlated with soil loss in an agricultural watershed than a forested watershed, and Faga'alu is mainly covered in dense forest. P was measured near the quarry (RG1), which may reflect precipitation characteristics more accurately in the Lower than the Upper watershed, and account for the lower correlation coefficients between SSY_{EV_UPPER} and Psum and EI. SSY_{LOWER} was hypothesized to be generated by sheetwash and rill formation at the quarry and agricultural plots, whereas SSY_{UPPER} was hypothesized to be from channel processes and mass wasting. Mass wasting can contribute large pulses of sediment which can be deposited near or in the streams and entrained at high discharges during later storm events.

The Q-SSC relationship (sediment rating curve) coefficients have no physical meaning, but the intercept (α) and slope (β) can be interpreted as a function of watershed characteristics (Asselman, 2000). Similarly, Rankl (2004) hypothesized that the intercept in the Qmax-SSY_{EV} relationship varied with the watershed's sediment availability and erodibility. While slopes in log-log space can be compared directly (Duvert et al., 2012), intercepts must be plotted in similar units and normalized by watershed area. Most studies do not correct storm metric-SSY models for log-bias, as is suggested by Ferguson (1986) for Q-SSC relationships, so we calculated the bias correction factor separately from the intercept (Equation 5) to compare our model slopes and intercepts with these other studies. In five semi-arid to arid watersheds (2.1 - 1,538 km^2) in Wyoming, United States, Qmax- SSY_{EV} relationship intercepts ranged from 111 - 4,320 (Qmax in $m^3/s/km^2$, SSY_{EV} in Mg/km^2) (Rankl, 2004). In eight sub-humid to semi-arid watersheds (0.45-22 km^2), intercepts ranged from 25-5,039 (Duvert et al., 2012). In Faga'alu, intercepts were 0.4 and 2.4 in the undisturbed and disturbed watersheds, respectively. These intercepts are 1-2 orders of magnitude lower than in Rankl (2004) and Duvert et al. (2012), suggesting that sediment availability is relatively low under natural and human-disturbed conditions in Faga'alu, likely due to the dense forest cover.

High slope values in the log-log plots (β coefficient) suggest that small increases in stream discharge correlate with large increases in sediment load due to the erosive power of the stream or the availability of new sediment sources at high Q (Asselman, 2000). Rankl (2004) assumed that the slope was a function of rainfall intensity on hillslopes and found that the slopes were not statistically different among watersheds and ranged from 1.07-1.29 in semi-arid Wyoming. In watersheds in Duvert et al. (2012), slopes ranged from 0.95-1.82, and from 1.06-2.45 in eighteen other watersheds (0.60-1,538 km²) in diverse geographical settings (Basher et al., 1997; Fahey and Marden, 2000; Hicks et al., 2009; Rankl, 2004; Tropeano, 1991). In Faga'alu, slopes were 1.51 and 1.41 in the undisturbed and disturbed watersheds, respectively. These slopes are consistent with the slopes in Rankl (2004) and Duvert et al. (2012), despite large differences in climate and land cover.

5.3 Estimation of annual SSY: comparison with other tropical islands

Sediment yield is highly variable among watersheds, but is generally controlled by climate, vegetation cover, and geology, with human disturbance playing an increasing role in the 20th century (Syvitski et al., 2005). Sediment yields in tropical Southeast Asia and high-standing islands between Asia and Australia range from ~10 tons/km²/yr in the granitic Malaysian Peninsula to ~10,000 tons/km²/yr in the tectonically active, steeply sloped island of Papua New Guinea (Douglas, 1996). Sediment yields from Faga'alu are on the lower end of the range, with sSSY of 45-143 tons/km²/yr from the undisturbed Upper watershed, and 241-368 tons/km²/yr from the disturbed Total watershed (estimated from Qmax model with bias correction and Equation 6 with all events).

Milliman and Syvitski (1992) report high average sSSY (1,000-3,000 tons/km²/yr) from watersheds (10-100,000 km²) in tropical Asia and Oceania. Their regional models of sSSY as a function of basin size and maximum elevation were not corrected for log-transform bias, but predict only 13 tons/km²/yr from watersheds with peak elevation 500-1,000 m (highest point of Upper Faga'alu subwatershed is 653 m), and 68 tons/km²/yr for max elevations of 1,000-3,000 (Table 8). Given the high vegetation cover and lack of human disturbance in the Upper subwatershed, sSSY is expected to be lower than watersheds presented in Milliman and Syvitski (1992), but sSSY (uncorrected for log-transform bias) from the forested Upper Faga'alu subwatershed (45-68 tons/km²/yr) was approximately three to five times higher than the prediction from the Milliman and Syvitski (1992) model (13 tons/km²/yr). There is large scatter around their model for smaller watersheds, and the Faga'alu data fall within the range of scatter (Figures 5e and 6e in Milliman and Syvitski (1992)). Faga'alu is also a much smaller watershed and the study period was relatively short (3 years) compared to others included in their models.

SSY was measured from two Hawaiian watersheds which are physiographically similar though much larger than Faga'alu,: Hanalei watershed on Kauai ("Hanalei", 54 km²), and Kawela watershed on Molokai ("Kawela", 14 km²) (Table 8) (Ferrier et al., 2013; Stock and Tribble, 2010). Hanalei had slightly higher rainfall (3,866 mm/yr) than Faga'alu (3,247 mm/yr) but slightly lower SSC (mean 63 mg/L, maximum of 2,750 mg/L) than the Total Faga'alu watershed (mean 148 mg/L, maximum 3,500 mg/L) (Ferrier et al., 2013; Stock and Tribble, 2010). Kawela is drier than Faga'alu (P varies with elevation from 500-3,000 mm) and had much higher SSC (mean 3,490 mg/L, maximum 54,000 mg/L) than the Total Faga'alu watershed. SSY from Hanalei was 369 ± 114 tons/km^2/yr (Ferrier et al., 2013), which is higher than the undisturbed subwatershed in Faga'alu (45-143 tons/km^2/yr) but similar to the disturbed Lower (441-598 tons/km^2/yr) subwatersheds. Stock and Tribble (2010) estimated SSY from Kawela was 459 tons/km²/yr, similar to the disturbed Lower Faga'alu watershed, but higher than the Total Faga'alu watershed (241-368 tons/km^2/yr). Overall, both Hawaiian watersheds have higher SSY than Faga'alu, which is consistent with the low Qmax-SSY_{EV} intercepts and suggests Faga'alu has relatively low erosion rates for a steep, volcanic watershed. Precipitation variability may contribute to the difference in SSY, so a more thorough comparison between Hanalei and Faga'alu would require a storm-wise analysis of the type performed here.

<Table 8 here please>

6. Conclusion

Human disturbance has increased sediment yield to Faga'alu Bay by 3.9x over pre-disturbance levels. The human-disturbed subwatershed accounted for the majority (87%) of Total sediment yield, and the quarry (1.1% of watershed area) contributed about a third of Total SSY to the Bay. The anthropogenic impact on SSY_{EV} may vary by storm magnitude, as documented in Pacific Northwest forests (Lewis et al., 2001), but the storm metric models developed here showed contradictory results. Qmax was a good predictor of SSY_{EV} in both the disturbed and undisturbed watersheds, making it a promising predictor in diverse environments. The slopes of the Qmax-SSY_{EV} relationships were comparable with other studies, but the model intercepts were an order of magnitude lower than intercepts from watersheds in semi-arid to semi-humid climates. This suggests that sediment availability is relatively low in the Faga'alu watershed, either because of the heavy forest cover or volcanic rock type.

This study presents an innovative method to combine sampling and analysis strategies to measure sediment contributions from key sources, estimate baseline annual sediment yields prior to management, and rapidly develop an empirical sediment yield model for a remote, data-poor watershed. While the instantaneous Q-SSC relationship illustrated large increases in SSC downstream of the quarry, the hysteresis and interstorm variability meant that a single Q-SSC relationship could not be used to estimate sediment loading, which is common in many watersheds (Asselman, 2000; Stock and Tribble, 2010). From a management perspective, the event-wise approach was useful for determining change over space and time without the problem of interannual variability in precipitation or the need for continuous, multi-year monitoring in a remote area. This approach is less expensive than efforts to measure annual yields and can be rapidly conducted if mitigation or disturbance activities are already planned.

Acknowledgements

Funding for this project was provided by NOAA Coral Reef Conservation Program (CRCP) through the American Samoa Coral Reef Advisory Group (CRAG). Kristine Bucchianeri at CRAG and Susie Holst at NOAA CRCP provided significant support. Christianera Tuitele, Phil Wiles, and Tim Bodell at American Samoa Environmental Protection Agency (ASEPA), and Fatima Sauafea-Leau and Hideyo Hattori at NOAA, provided on-island coordination with traditional local authorities. Dr. Mike Favazza provided critical logistical assistance in American Samoa. Robert Koch at the American Samoa Coastal Zone Management Program (ASCMP) and Travis Bock at ASEPA assisted in accessing historical geospatial and water quality data. Professor Jameson Newtson, Rocco Tinitali, and Valentine Vaeoso at American Samoa Community College (ASCC), Meagan Curtis and Domingo Ochavillo at American Samoa Department of Marine and Wildlife Resources (DMWR), Don and Agnes Vargo at American Samoa Land Grant, Christina Hammock at NOAA American Samoa Climate Observatory, and Greg McCormick at San Diego State University supported the field and laboratory work. George Poysky, Jr., George Poysky III, and Mitch Shimisaki at Samoa Maritime Ltd. provided unrestricted access to the Faga'alu quarry, and historical operation information. Faafetai tele lava.

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Figure
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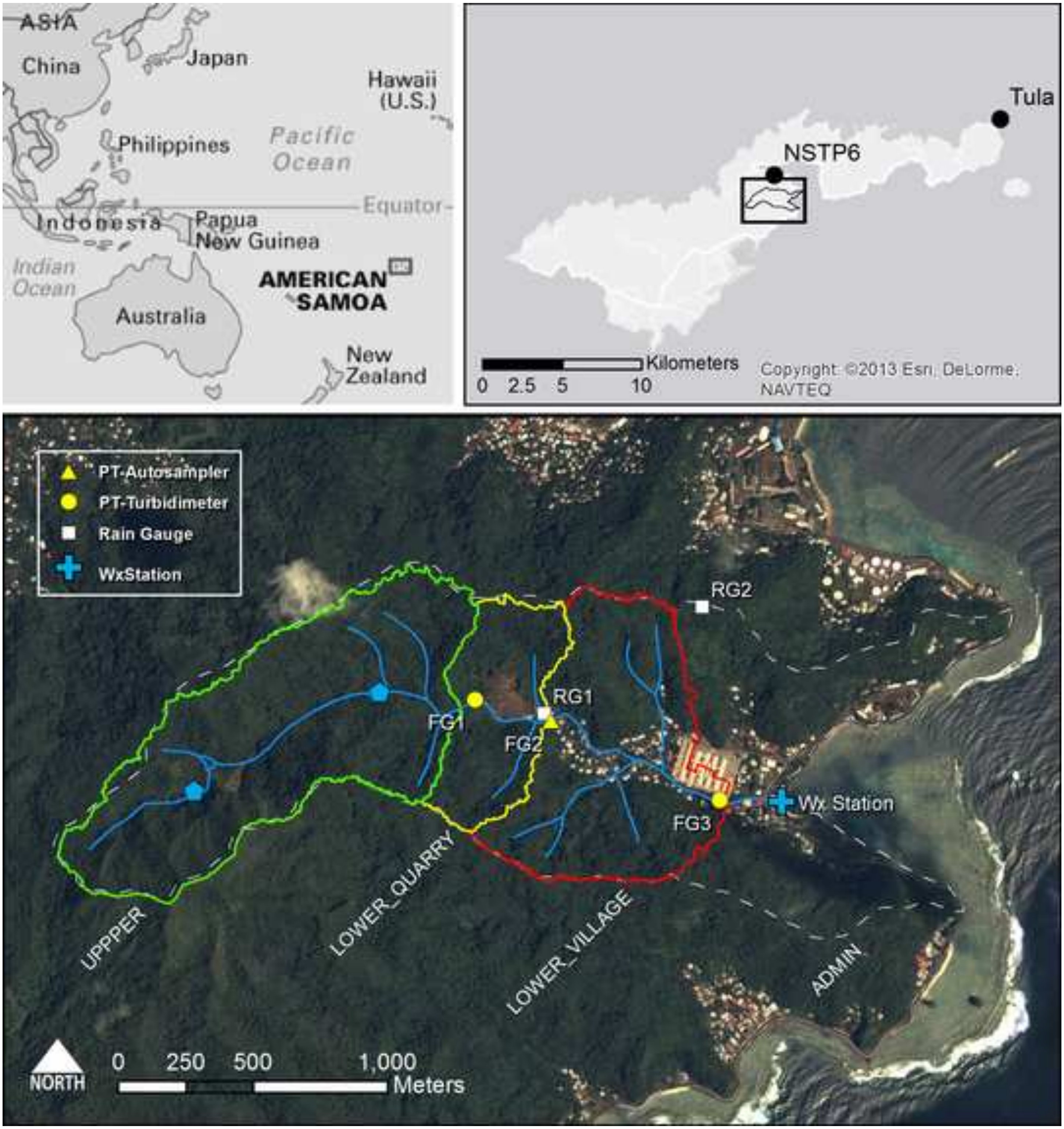

Figure
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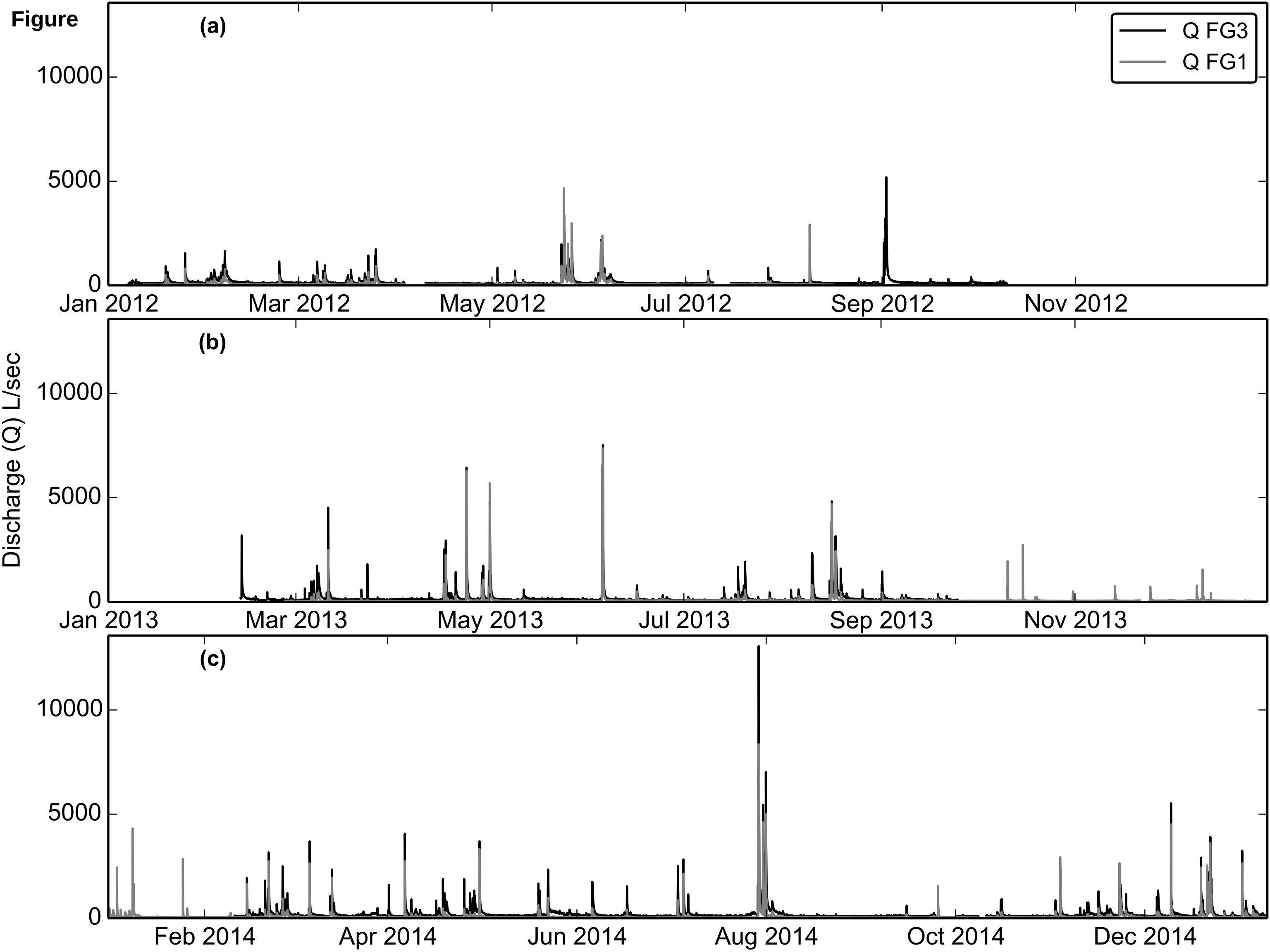
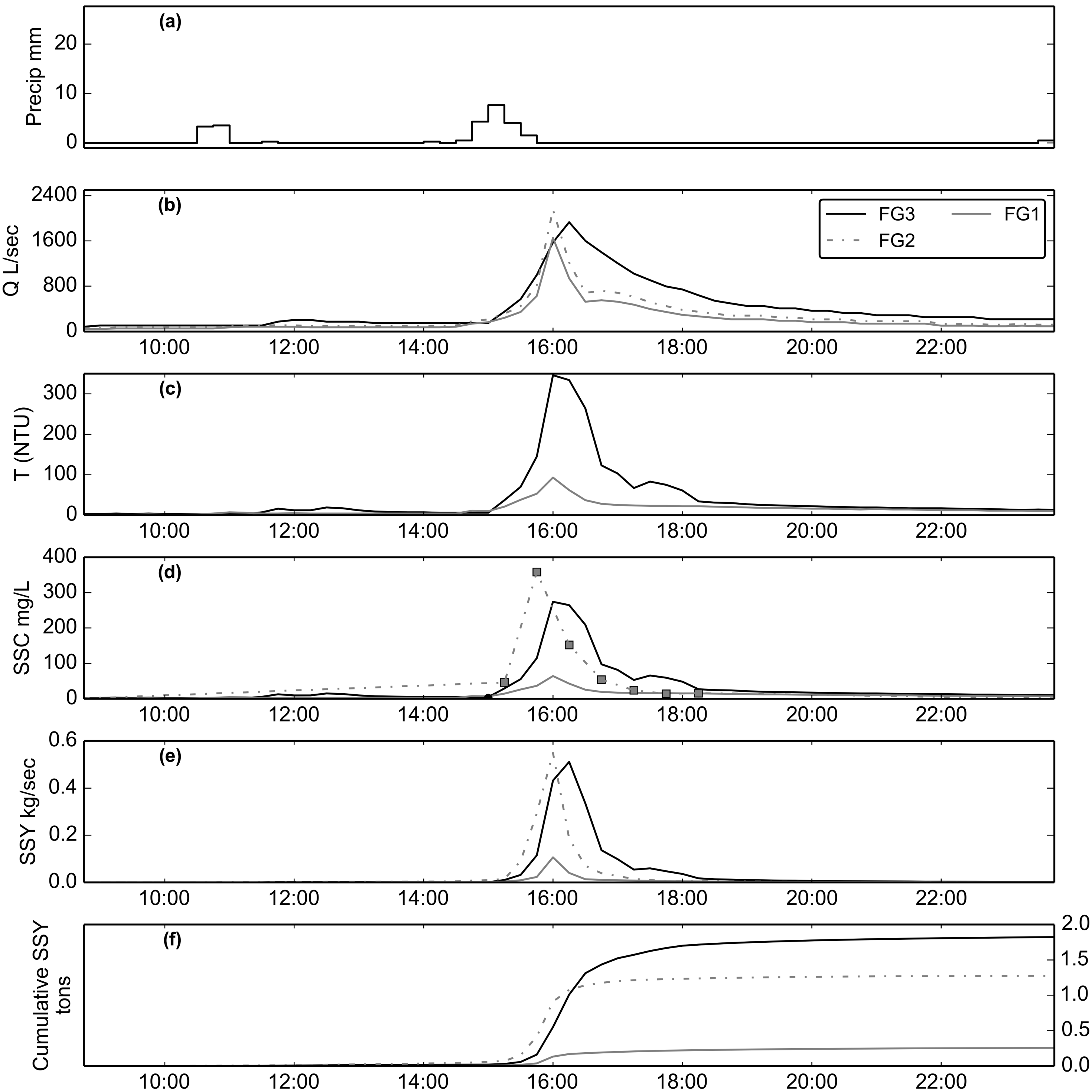
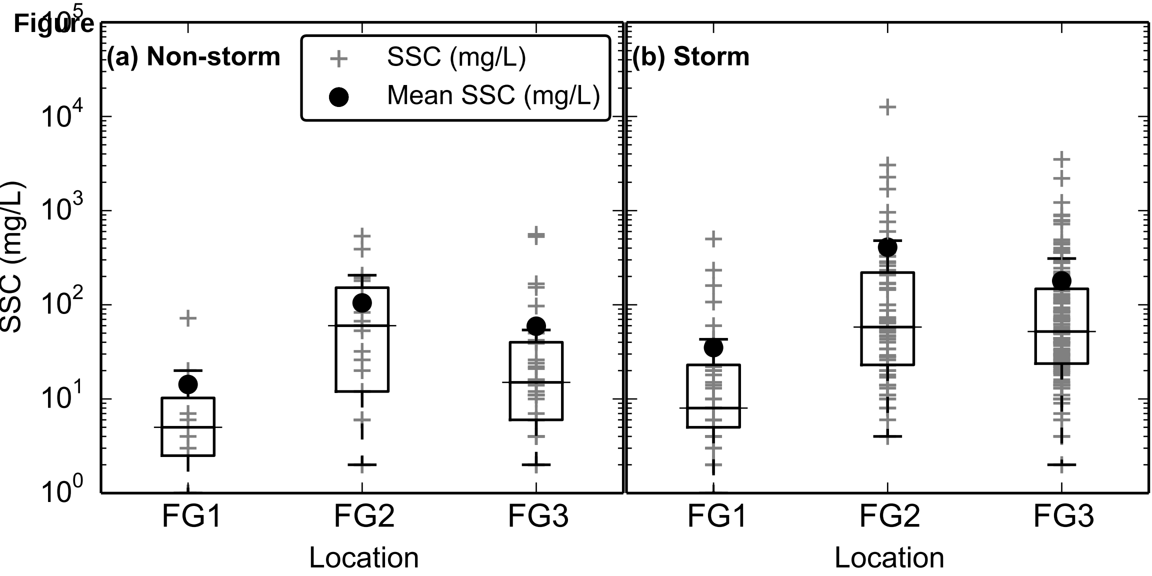
Figure


(a)
Q FG3
Q FG1
10000
5000
0
Jan 2012
Mar 2012
May 2012
Jul 2012
Sep 2012
Nov 2012
(b)
Discharge (Q) L/sec
10000
5000
0
Jan 2013
Mar 2013
May 2013
Jul 2013
Sep 2013
Nov 2013
(c)
10000
5000
0
Feb 2014
Apr 2014
Jun 2014
Aug 2014
Oct 2014
Dec 2014

Figure


(a)
Precip mm
0
10
20
(b)
Q L/sec
0
800
1600
2400
FG3
FG1
FG2
10:00
12:00
14:00
16:00
18:00
20:00
22:00
(c)
T (NTU)
0
100
200
300
(d)
SSC mg/L
0
100
200
300
400
(e)
SSY kg/sec
0.0
0.2
0.4
0.6
(f)
Cumulative SSY tons
0.0
0.5
1.0
1.5
2.0

Figure



(a) Non-storm
(b) Storm
SSC (mg/L)
Mean SSC (mg/L)
SSC (mg/L)
10^0
10^1
10^2
10^3
10^4
10^5
FG1
FG2
FG3
FG1
FG2
FG3
Location
Location

Figure

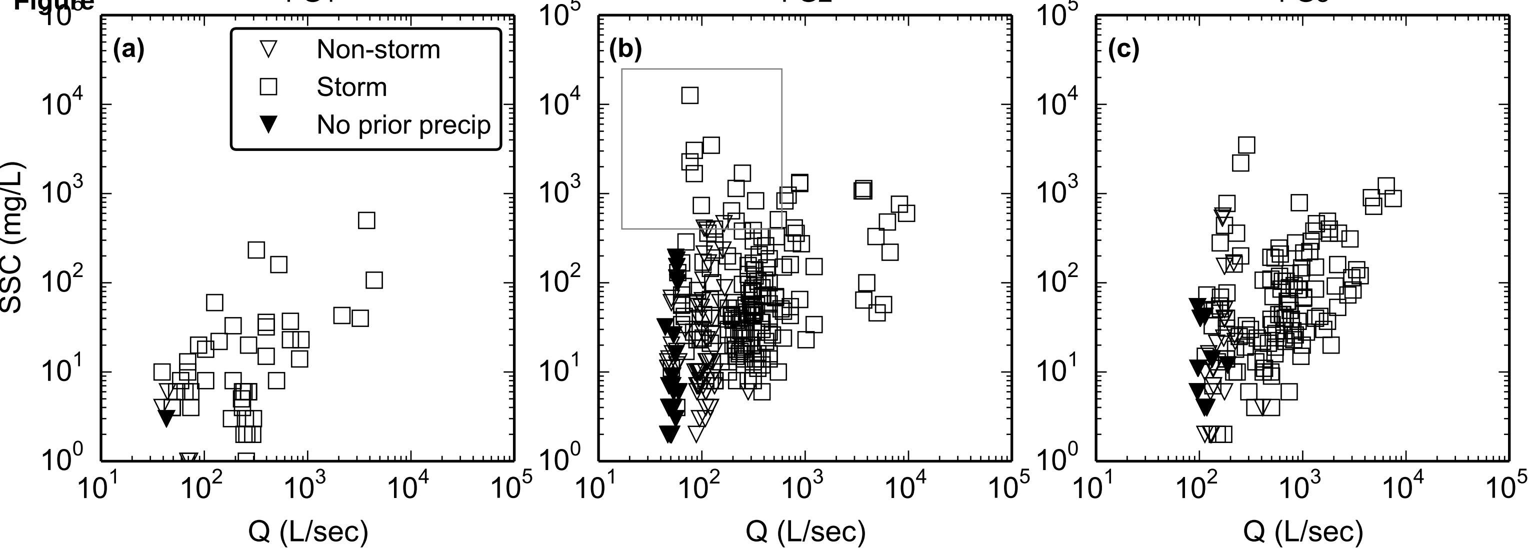
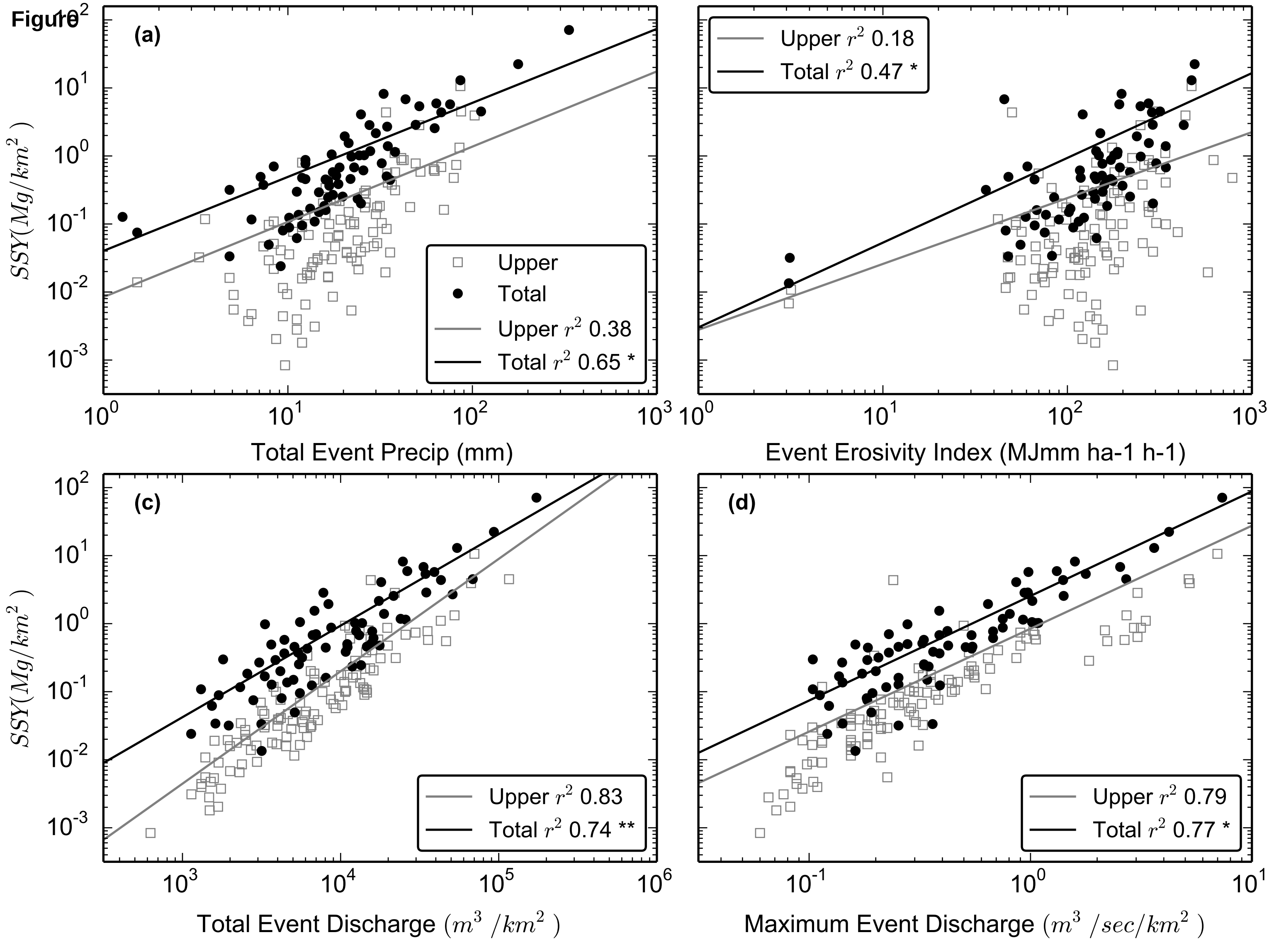
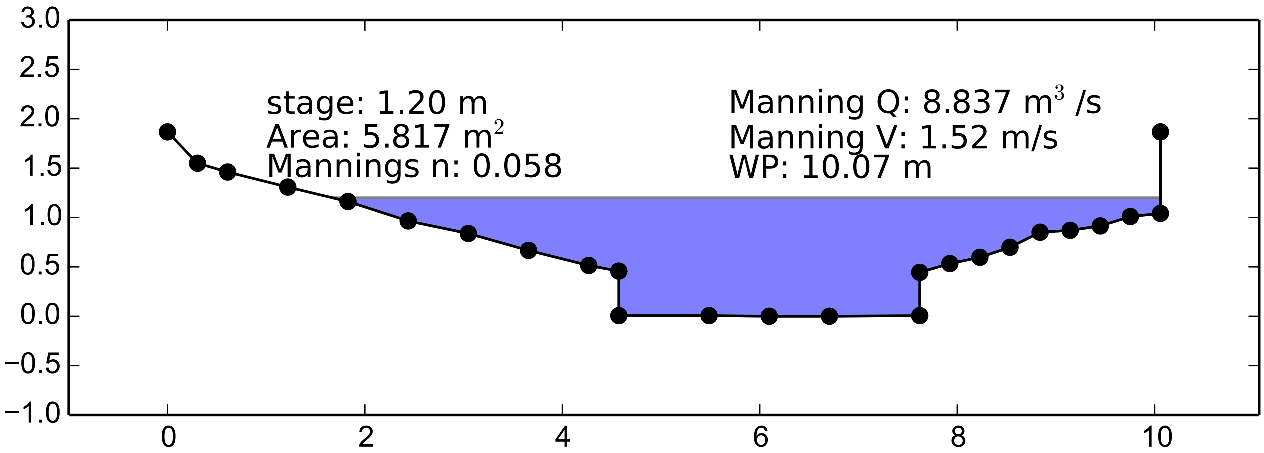

FG1
FG2
FG3
(a)
(b)
(c)
Non-storm
Storm
No prior precip
SSC (mg/L)
Q (L/sec)
Q (L/sec)
Q (L/sec)
10^0
10^1
10^2
10^3
10^4
10^5
10^6

Figure6



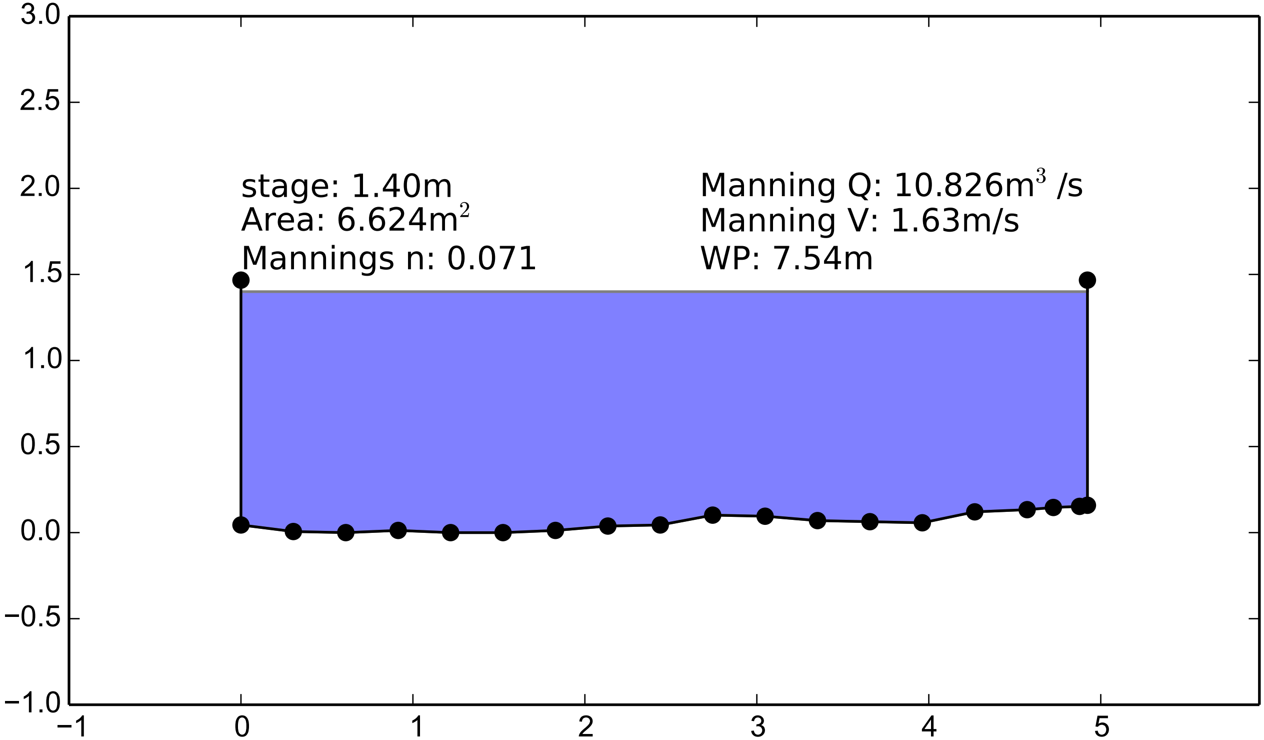
(a)
Upper
Total
Upper r^2 0.38
Total r^2 0.65 *
Upper r^2 0.18
Total r^2 0.47 *
(c)
Upper r^2 0.83
Total r^2 0.74 **
(d)
Upper r^2 0.79
Total r^2 0.77 *
$SSY(Mg/km^2)$
Total Event Precip (mm)
Event Erosivity Index (MJmm ha-1 h-1)
Total Event Discharge (m^3/km^2)
Maximum Event Discharge $(m^3/sec/km^2)$

Figure



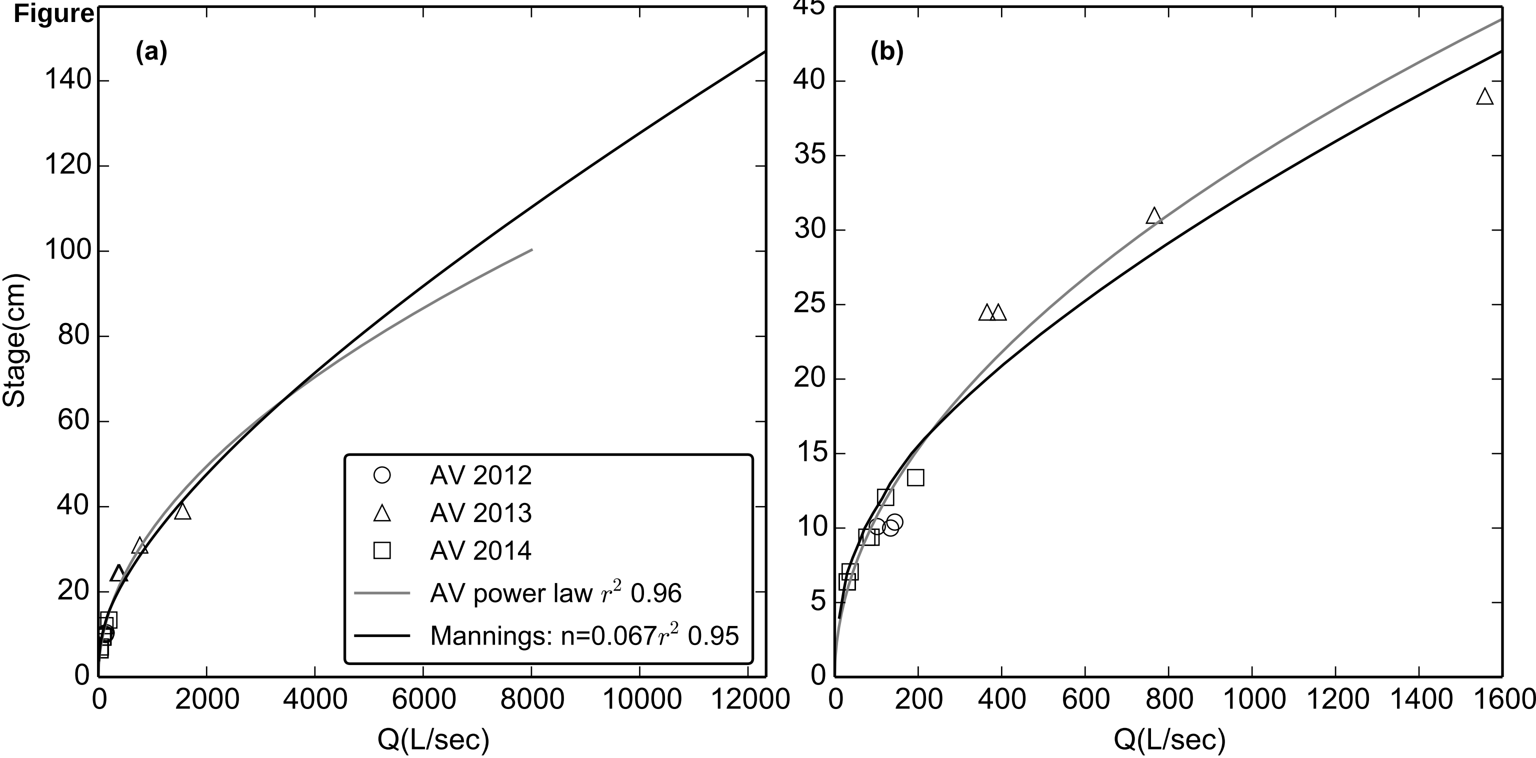
stage: 1.20 m
Area: 5.817 m²
Mannings n: 0.058
Manning Q: 8.837 m³ /s
Manning V: 1.52 m/s
WP: 10.07 m
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
0
2
4
6
8
10

Figure



stage: 1.40m
Area: 6.624m^2
Mannings n: 0.071
Manning Q: 10.826m^3 /s
Manning V: 1.63m/s
WP: 7.54m
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1
0
1
2
3
4
5

Figure



(a)
(b)
Stage(cm)
Q(L/sec)
Q(L/sec)
AV 2012
AV 2013
AV 2014
AV power law r^2 0.96
Mannings: n=0.067r^2 0.95

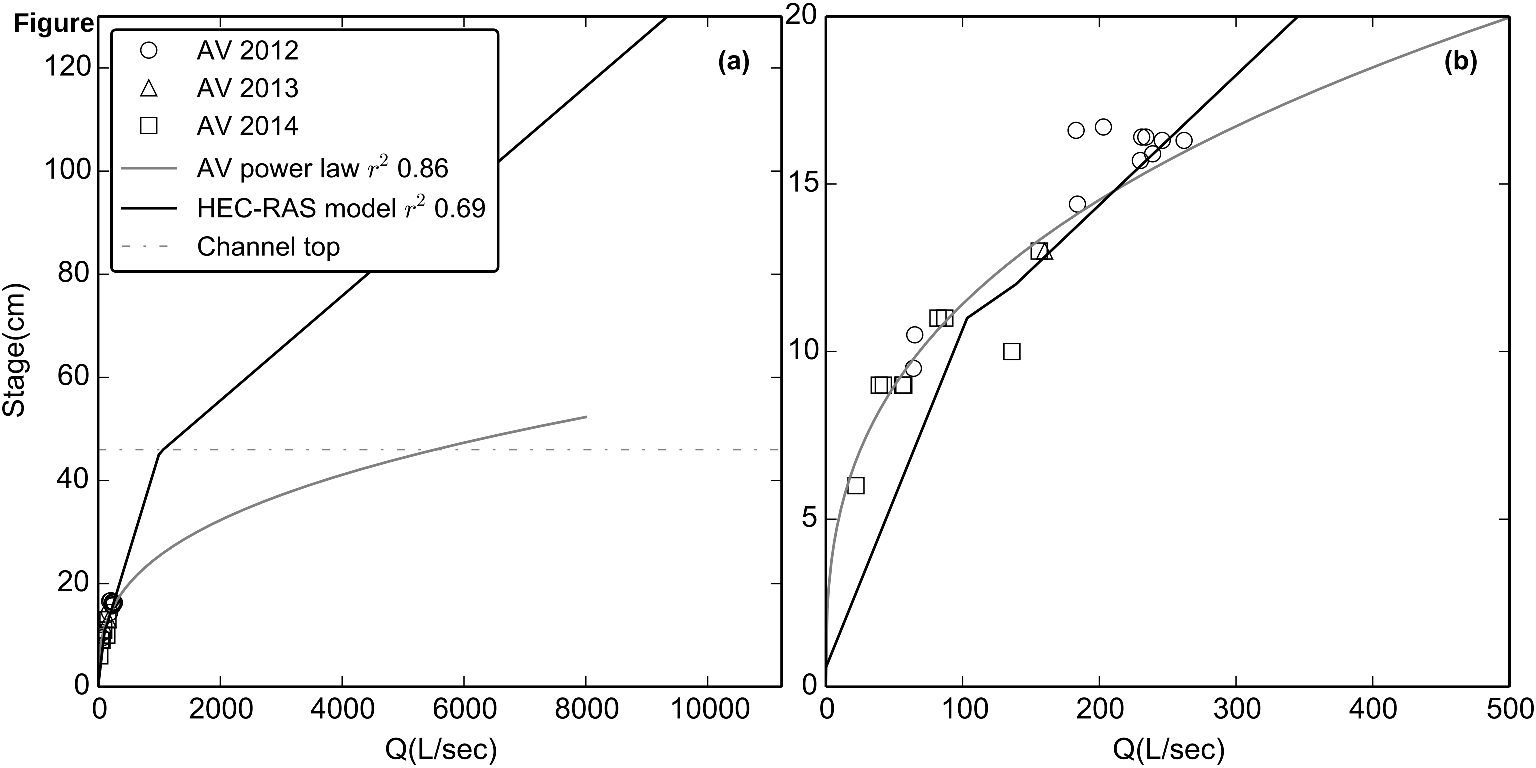
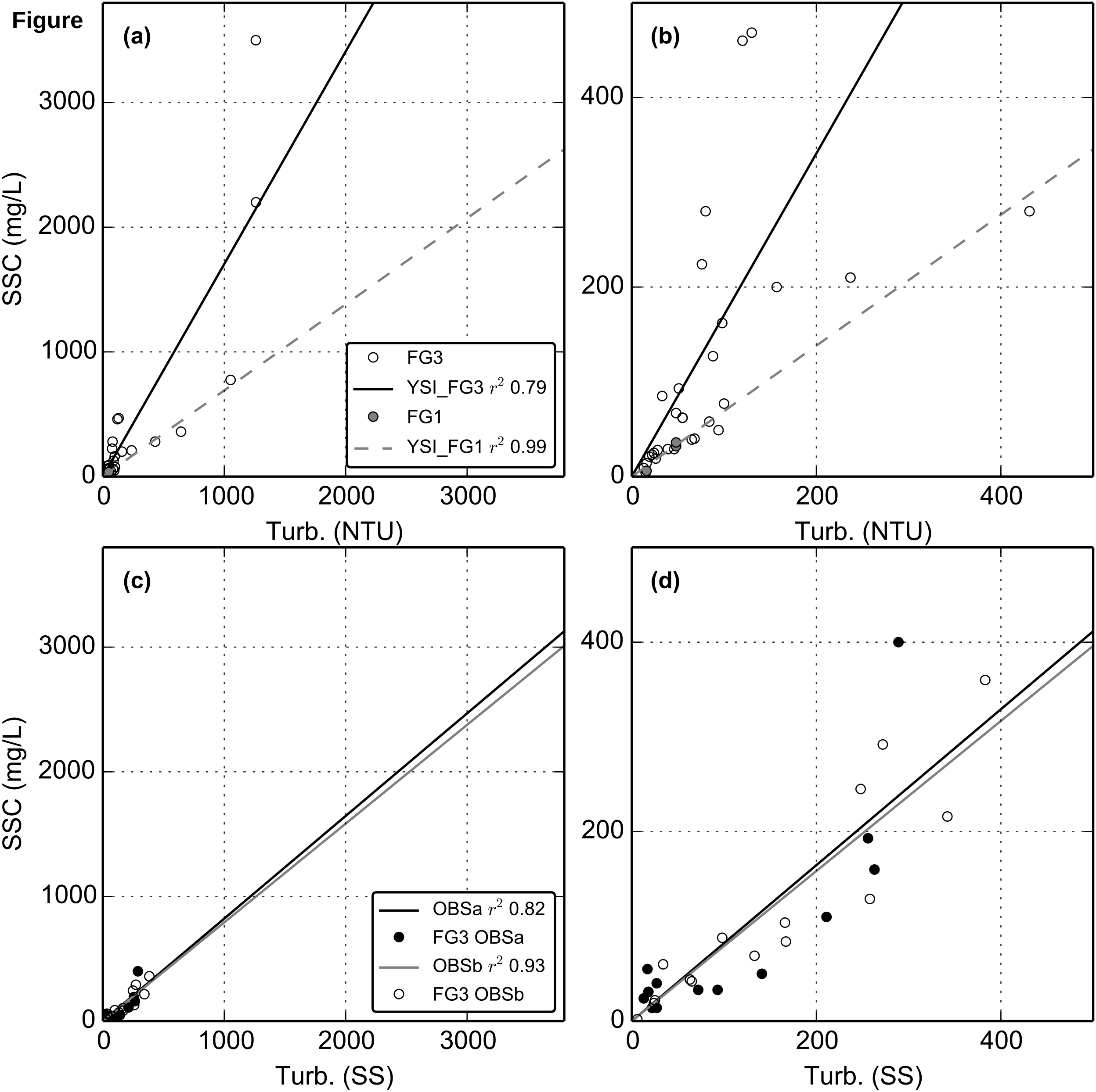


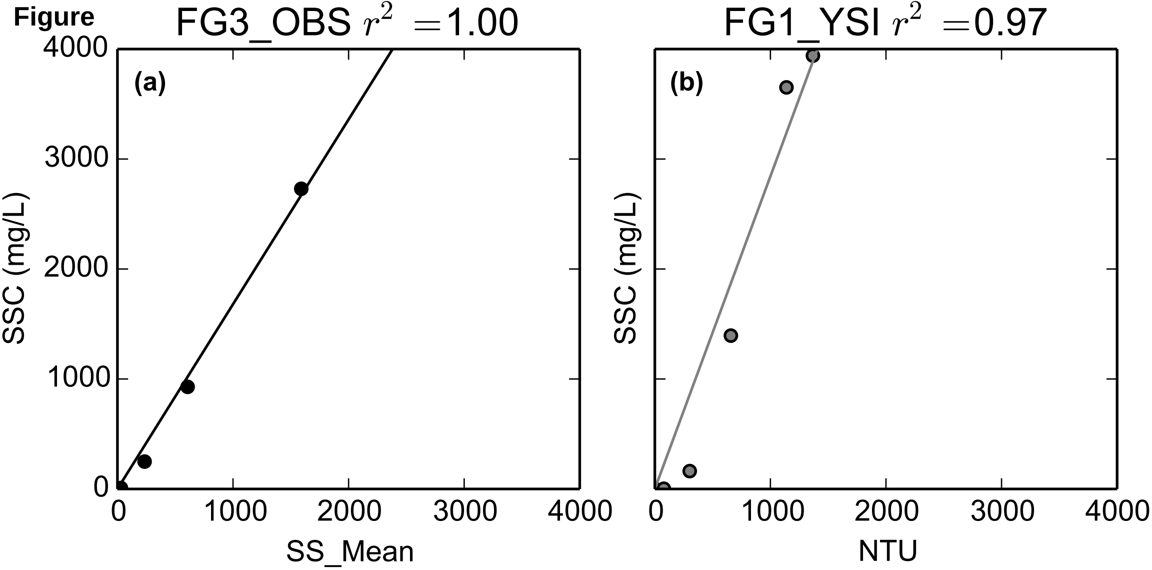
Figure
AV 2012
AV 2013
AV 2014
AV power law r^2 0.86
HEC-RAS model r^2 0.69
Channel top
(a)
(b)
Stage(cm)
Q(L/sec)
Q(L/sec)

Figure



(a)
(b)
(c)
(d)
SSC (mg/L)
Turb. (NTU)
Turb. (SS)
FG3
YSI_FG3 r^2 0.79
FG1
YSI_FG1 r^2 0.99
OBSa r^2 0.82
FG3 OBSa
OBSb r^2 0.93
FG3 OBSb
0
1000
2000
3000
200
400

Figure



FG3_OBS r^2 =1.00
(a)
SSC (mg/L)
SS_Mean
0
1000
2000
3000
4000
FG1_YSI r^2 =0.97
(b)
SSC (mg/L)
NTU

Figure

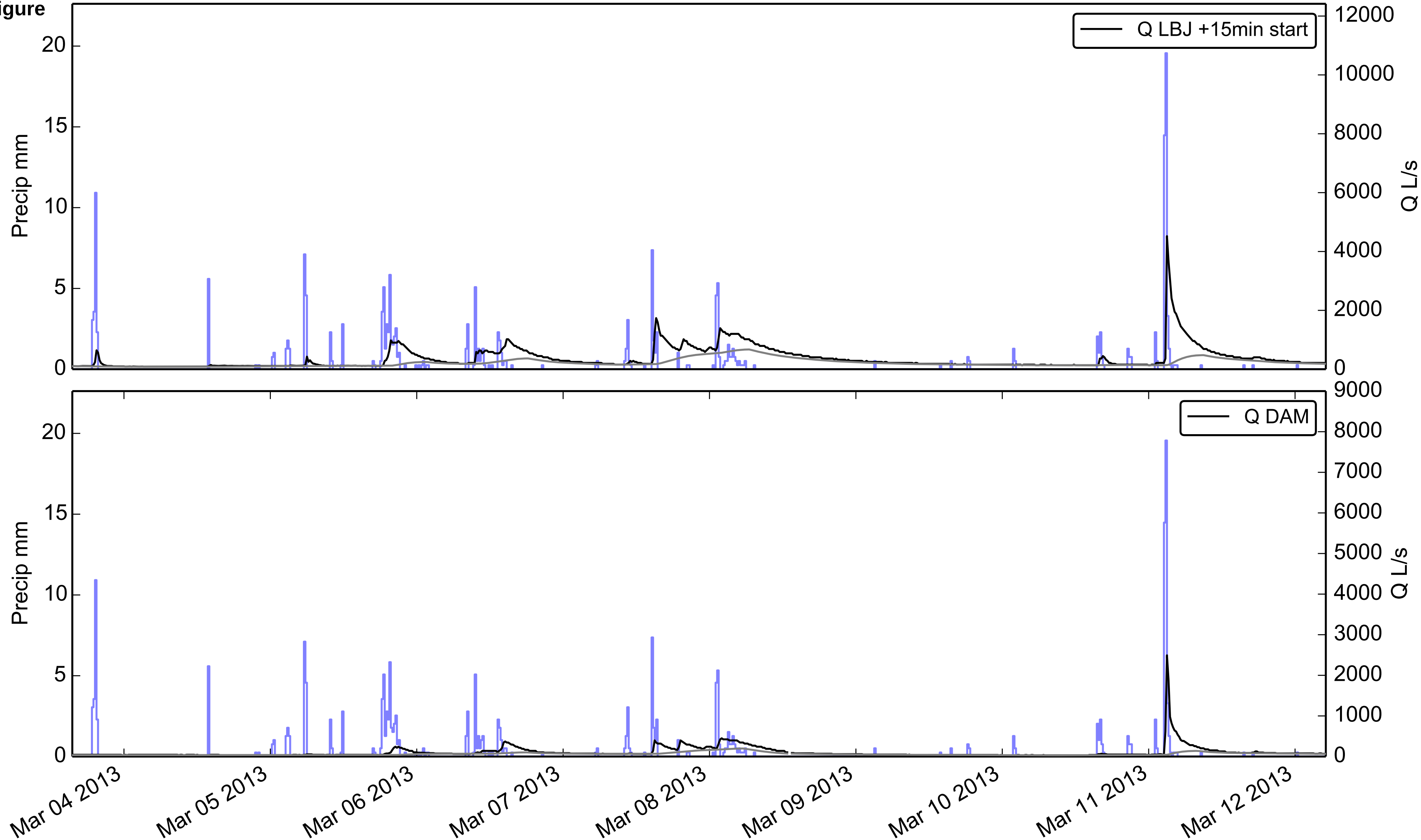

Q LBJ +15min start
Precip mm
Q L/s
0
5
10
15
20
0
2000
4000
6000
8000
10000
12000
Q DAM
Precip mm
Q L/s
0
5
10
15
20
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
Mar 04 2013
Mar 05 2013
Mar 06 2013
Mar 07 2013
Mar 08 2013
Mar 09 2013
Mar 10 2013
Mar 11 2013
Mar 12 2013

Table 1. Land use categories in Faga'alu subwatersheds (NOAA Ocean Service and Coastal Services Center, 2010). Land cover percentages are of the subwatershed.

Subwatershed (outlet)	Cumulative Area		Subwatershed Area		Land cover as % subwatershed area [a]							
	km^2	%	km^2	%	B	HI	DOS	GA	F	S	Disturbed	Undisturbed
Upper (FG1)	0.9	50	0.90	50	0.4	0.0	0.0	0.1	82	17.1	0.4	100
Lower_Quarry (FG2)	1.2	66	0.27	16	5.7	0.7	0.1	0.5	92	0.9	6.5	94
Lower_Village (FG3)	1.8	100	0.60	34	0.0	9.0	2.6	0.2	88	0.6	11.7	88
Lower (FG3)	1.8	100	0.88	50	1.8	6.4	1.8	0.3	89	0.7	10.1	90
Total (FG3)	1.8	100	1.78	100	1.1	3.2	0.9	0.2	86	9.0	5.2	95

a. B=Bare, HI=High Intensity Developed, DOS=Developed Open Space, GA=Grassland (agriculture), F=Forest, S=Scrub/Shrub, Disturbed=B+HI+DOS+GA, Undisturbed=F+S

b. Disturbed area for Upper was from natural landslide. Undisturbed is 100% from rounding up.

Table 2. Event-wise suspended sediment yield (SSY_{EV}) from subwatersheds in Faga'alu for events with simultaneous data from FG1 and FG3. Storm numbers correspond with the storms presented in Appendix C Table 1.

	Storm	Precip	SSY_{EV} tons			% of SSY_{EV_TOTAL}		PE[a]		SSC	
Storm#	Start	mm	Upper[b]	Lower[c]	Total[d]	Upper	Lower	Upper	Total	Data Source Upper	Data Source Total
2	01/19/2012	18	0.06	0.63	0.69	8.0	91.0	56	36	T-TS	int. grab
4	01/31/2012	35	0.03	1.92	1.95	1.0	98.0	56	118	T-TS	T-YSI
5	02/01/2012	11	0.01	0.4	0.42	3.0	96.0	56	118	T-TS	T-YSI
6	02/02/2012	16	0.06	1.02	1.08	5.0	94.0	56	118	T-TS	T-YSI
7	02/03/2012	11	0.08	2.01	2.09	3.0	96.0	56	118	T-TS	T-YSI
8	02/04/2012	6	0.0	0.51	0.51	0.0	99.0	56	118	T-TS	T-YSI
9	02/05/2012	23	0.05	0.98	1.03	5.0	94.0	56	118	T-TS	T-YSI
10	02/05/2012	21	0.09	1.93	2.02	4.0	95.0	56	118	T-TS	T-YSI
11	02/06/2012	38	0.28	4.75	5.03	5.0	94.0	56	118	T-TS	T-YSI
12	02/07/2012	4	0.01	0.13	0.15	9.0	90.0	56	118	T-TS	T-YSI
13	02/07/2012	10	0.03	0.51	0.54	5.0	94.0	56	118	T-TS	T-YSI
14	02/13/2012	11	0.0	0.27	0.27	1.0	98.0	56	118	T-TS	T-YSI
16	03/05/2012	22	0.0	4.39	4.4	0.0	99.0	56	118	T-TS	T-YSI
17	03/06/2012	56	0.19	9.05	9.25	2.0	97.0	56	118	T-TS	T-YSI
18	03/08/2012	22	0.09	2.89	2.98	2.0	97.0	56	118	T-TS	T-YSI
19	03/09/2012	19	0.2	2.78	2.97	6.0	93.0	56	118	T-TS	T-YSI
20	03/15/2012	17	0.01	1.17	1.18	0.0	99.0	56	118	T-TS	T-YSI
21	03/16/2012	34	0.08	2.12	2.2	3.0	96.0	56	118	T-TS	T-YSI
22	03/17/2012	32	0.09	3.33	3.43	2.0	97.0	56	118	T-TS	T-YSI
23	03/20/2012	24	0.04	0.84	0.88	4.0	95.0	56	118	T-TS	T-YSI
24	03/21/2012	18	0.2	2.06	2.26	8.0	91.0	56	118	T-TS	T-YSI
25	03/22/2012	34	0.37	5.75	6.12	5.0	94.0	56	118	T-TS	T-YSI
27	03/24/2012	7	0.03	0.19	0.22	12.0	87.0	56	118	T-TS	T-YSI
28	03/25/2012	49	0.7	11.92	12.62	5.0	94.0	56	118	T-TS	T-YSI
29	03/31/2012	15	0.03	0.78	0.81	3.0	96.0	56	118	T-TS	T-YSI
32	05/07/2012	11	0.0	1.31	1.31	0.0	99.0	56	118	T-TS	T-YSI
33	05/08/2012	21	0.13	6.65	6.79	1.0	98.0	56	118	T-TS	T-YSI
34	05/20/2012	13	0.0	0.47	0.48	0.0	99.0	56	118	T-TS	T-YSI
64	04/16/2013	62	0.54	4.01	4.55	11.0	88.0	40	36	int. grab	int. grab
70	04/23/2013	86	9.57	13.51	23.08	41.0	58.0	40	36	int. grab	int. grab
79	06/24/2013	9	0.01	0.13	0.14	7.0	92.0	43	77	T-YSI	T-OBS
80	07/02/2013	13	0.02	0.28	0.3	5.0	94.0	43	77	T-YSI	T-OBS
106	02/14/2014	25	0.26	1.57	1.82	14.0	85.0	43	51	T-YSI	T-OBS
107	02/15/2014	7	0.04	0.63	0.67	6.0	93.0	43	51	T-YSI	T-OBS
109	02/18/2014	12	0.01	0.81	0.81	0.0	99.0	43	51	T-YSI	T-OBS
110	02/20/2014	29	0.13	3.71	3.84	3.0	96.0	43	51	T-YSI	T-OBS
111	02/21/2014	51	2.55	7.03	9.58	26.0	73.0	43	51	T-YSI	T-OBS
112	02/24/2014	16	0.09	0.56	0.65	13.0	86.0	43	51	T-YSI	T-OBS
113	02/24/2014	1	0.01	0.12	0.13	9.0	90.0	43	51	T-YSI	T-OBS
114	02/25/2014	67	0.62	7.17	7.79	7.0	92.0	43	51	T-YSI	T-OBS
115	02/27/2014	16	0.13	0.68	0.8	15.0	84.0	43	51	T-YSI	T-OBS
116	02/27/2014	12	0.12	1.25	1.37	8.0	91.0	43	51	T-YSI	T-OBS
Total/Avg	42	1004	17.0	112.2	129.2	13	87	52	94	-	-
Tons/km2	-	-	18.8	127.5	72.6	-	-	-	-	-	-
DR	-	-	1	6.8	3.9	-	-	-	-	-	-

a. PE is cumulative probable error (Eq 4) as a percentage of the mean observed SSY_{EV}.

b. Measured SSY_{EV} at FG1.

c. SSY_{EV} at FG3 - SSY_{EV} at FG1.

d. Measured SSY_{EV} at FG3.

Table 3. Suspended sediment yield (SSY), specific suspended sediment yield (sSSY), and disturbance ratio (DR) from disturbed portions of Upper and Lower subwatersheds for the storm events in Table 2.

	Upper[a]	**Lower**	**Total**
Fraction of subwatershed area disturbed (%)	0.4	10.1	5.2
SSY (tons)	17.0	112.2	129.2
Forested areas	16.9	14.9	31.7
Disturbed areas	0.1	97.3	97.5
% from disturbed areas	0.9	87	75
sSSY, disturbed areas (tons/km^2)	41.0	1095.0	1053.1
DR for sSSY from disturbed areas[b]	2	58	56

a. Disturbed areas in Upper are bare areas from landslides.

b. Calculated as (sSSY from disturbed areas)/sSSY from Upper (17.0 tons/km^2)

Table 4. Event-wise suspended sediment yield (SSY_{EV}) from subwatersheds in Faga'alu for events with simultaneous data from FG1, FG2, and FG3. Storm numbers correspond with the storms presented in Table 2 and Appendix C Table 1.

	Storm	Precip	SSY_{EV} tons					% of SSY_{EV_TOTAL}			
Storm#	**Start**	**mm**	**Upper[a]**	**Lower_Quarry[b]**	**Lower_Village[c]**	**Lower[d]**	**Total[e]**	**Upper**	**Lower_Quarry**	**Lower_Village**	**Lower**
2	01/19/2012	18	0.06	0.3	0.33	0.63	0.69	8.0	43.0	47.0	91.0
64	04/16/2013	62	0.54	2.77	1.24	4.01	4.55	11.0	60.0	27.0	88.0
70	04/23/2013	86	9.57	8.21	5.3	13.51	23.08	41.0	35.0	22.0	58.0
106	02/14/2014	25	0.26	1.01	0.55	1.57	1.82	14.0	55.0	30.0	86.0
110	02/20/2014	29	0.13	1.6	2.11	3.71	3.84	3.0	41.0	54.0	96.0
111	02/21/2014	51	2.55	2.07	4.96	7.03	9.58	26.0	21.0	51.0	73.0
115	02/27/2014	16	0.13	0.08	0.59	0.68	0.8	16.0	9.0	73.0	85.0
116	02/27/2014	12	0.12	0.32	0.93	1.25	1.37	8.0	23.0	67.0	91.0
Total/Avg	8	299	13.4	16.4	16.0	32.4	45.7	29	36	35	71
Tons/km2			14.8	60.6	26.7	36.8	25.7	-	-	-	-
DR			1.0	4.08	1.8	2.5	1.7	-	-	-	-

a. Measured SSY_{EV} at FG1.
b. SSY_{EV} at FG2 - SSY_{EV} at FG1.
c. SSY_{EV} at FG3 - SSY_{EV} at FG2.
d. SSY_{EV} at FG3 - SSY_{EV} at FG1.
e. Measured SSY_{EV} at FG3.

Table 5. Suspended sediment yield (SSY), specific suspended sediment yield (sSSY), and disturbance ratio (DR) from disturbed portions of Upper, Lower_Quarry, and Lower_Village subwatersheds for the storm events in Table 4.

	Upper	Lower_Quarry	Lower_Village	Lower	Total
Fraction of subwatershed area disturbed (%)	0.4	6.5	11.7	10.1	5.2
SSY (tons)	13.4	16.4	16.0	32.4	45.7
Forested areas	13.3	3.7	7.8	11.7	25.0
Disturbed areas	0.1	12.7	8.2	20.7	20.7
% from disturbed areas	1.0	77	51	64	45
sSSY, disturbed areas (tons/km^2)	37.0	721.6	116.2	232.8	223.9
DR for sSSY from disturbed areas	3	49	8	16	15

Table 6. Goodness-of-fit statistics for storm metric-SSY_{EV} relationships. Spearman correlation coefficients signifcant at p<0.01.

Model	Spearman	r^2	RMSE(tons)	Intercept(α)	Slope(β)	BCF
Psum_upper	0.70	0.39	4.31	0.003	1.10	2.71
Psum_total	0.88	0.71	2.43	0.033	1.11	1.39
EI_upper	0.48	0.18	5.48	0.001	0.97	4.38
EI_total	0.73	0.55	2.98	0.001	1.32	2.00
Qsum_upper	0.91	0.83	2.15	0.000	1.65	1.42
Qsum_total	0.83	0.70	2.46	0.000	1.29	1.50
Qmax_upper	0.90	0.79	2.36	0.398	1.51	2.12
Qmax_total	0.80	0.67	2.59	2.429	1.41	1.49

Table 7. Estimates of Annual SSY and sSSY calculated using four different methods

	Psum model, Events in 2014	Qmax model, Events in 2014	Equation 6		
			Events in Table 2	Events in Table 4	All Measured Events
Precipitation					
mm (% of Ps_{ann})	2770	2770	1004 (36%)	299 (11%)	3457 (125%)
Annual SSY (tons/year)					
Upper	35	129	46	120	41
Lower	152	526	310	300	388
Lower_Quarry	-	-	-	150	-
Lower_Village	-	-	-	150	-
Total	187	655	360	420	428
Annual sSSY (tons/km^2/year)					
Upper	39	143	51	140	45
Lower	679	598	350	340	441
Lower_Quarry	-	-	-	560	-
Lower_Village	-	-	-	250	-
Total	105	368	200	240	241

Table
Click here to download Table: Table8_Lit_values_for_SSY_bias_corrected.pdf

Table 8. Annual Specific Suspended Sediment Yield (sSSY) from steep, volcanic islands in the tropical Pacific.

Location	Watershed drainage area (km2)	Mean annual precipitation (mm)	sSSY range tons/km2/yr	Reference
Faga'alu UPPER	0.88		45-143	This study
Faga'alu TOTAL	1.78	2.380-6,350 (varies with elevation)	241-368	This study
Kawela, Molokai	13.5	500-3,000 (varies with elevation)	394	(Stock and Tribble, 2010)
Hanalei, Kauai	60.04	500 – 9,500 (varies with elevation)	545 ± 128	(Ferrier et al., 2013)
Hanalei, Kauai	48.4	2,000-11,000 (varies with elevation)	525	(Stock and Tribble, 2010)
Hanalei, Kauai	54.4	2,000-11,000 (varies with elevation)	140±55	(Calhoun and Fletcher, 1999)
St. John, USVI[a]	3.5	1,300-1,400	18	(Ramos-Scharrón and Macdonald, 2007)
St. John, USVI	2.3	1,300-1,400	24	(Nemeth and Nowlis, 2001)
St. John, USVI	6	1,300-1,400	36	(Nemeth and Nowlis, 2001)
Oahu	10.4	1,000-3,800 (varies with elevation)	330±130; 200±100 (varies with method)	(Hill et al., 1997)
Barro Colorado, Panama	0.033	2,623±458	100-200	(Zimmermann et al., 2012)
Fly River, PNG[b]	76,000	up to 10,000	1,000-1,500	(Milliman, 1995)
Purari River, PNG	35,000		3,000	"

Milliman and Syvitski (1992) Model:					
sSSY = cA^f					(Milliman and Syvitski, 1992)
c,f = regression coeff. for region/max elevation		**c**	f	**sSSY tons/km2/yr**	
Max elev >3,000m	Faga'alu UPPER = 0.88 TOTAL = 1.78	280	-0.54	UPPER = 296 TOTAL = 205	-
Max elev 1000-3000m (Oceania)		65	-0.46	UPPER = 68 TOTAL = 50	-
Max elev 500-1,000m		12	-0.59	UPPER = 13 TOTAL = 9	-

Table A3.1. Water discharge from subwatersheds in Faga'alu. Includes all storm events for 2012, 2013, and 2014.

Storm#	Storm Start	Precip mm	Discharge m^3			Percentage	
			Upper	Lower	Total	Upper	Lower
1	01/18/2012	70.0	10765.0	12319.0	23084.0	46.0	53.0
2	01/19/2012	18.0	8117.0	11055.0	19172.0	42.0	57.0
3	01/25/2012	79.0	17887.0	17125.0	35012.0	51.0	48.0
4	01/31/2012	35.0	6467.0	7868.0	14335.0	45.0	54.0
5	02/01/2012	11.0	4071.0	5767.0	9838.0	41.0	58.0
6	02/02/2012	16.0	9224.0	14750.0	23974.0	38.0	61.0
7	02/03/2012	11.0	12729.0	18682.0	31411.0	40.0	59.0
8	02/04/2012	6.0	1359.0	2765.0	4124.0	32.0	67.0
9	02/05/2012	23.0	8374.0	12716.0	21090.0	39.0	60.0
10	02/05/2012	21.0	9603.0	16471.0	26074.0	36.0	63.0
11	02/06/2012	38.0	20080.0	25795.0	45875.0	43.0	56.0
12	02/07/2012	4.0	2643.0	2970.0	5613.0	47.0	52.0
13	02/07/2012	10.0	5178.0	6536.0	11714.0	44.0	55.0
14	02/13/2012	11.0	1186.0	1548.0	2734.0	43.0	56.0
15	02/23/2012	17.0	11491.0	15655.0	27146.0	42.0	57.0
16	03/05/2012	22.0	1449.0	4629.0	6078.0	23.0	76.0
17	03/06/2012	56.0	13131.0	17173.0	30304.0	43.0	56.0
18	03/08/2012	22.0	6904.0	4946.0	11850.0	58.0	41.0
19	03/09/2012	19.0	12850.0	10482.0	23332.0	55.0	44.0
20	03/15/2012	17.0	2138.0	3305.0	5443.0	39.0	60.0
21	03/16/2012	34.0	8794.0	10815.0	19609.0	44.0	55.0
22	03/17/2012	32.0	9756.0	12562.0	22318.0	43.0	56.0
23	03/20/2012	24.0	3621.0	3782.0	7403.0	48.0	51.0
24	03/21/2012	18.0	13828.0	14072.0	27900.0	49.0	50.0
25	03/22/2012	34.0	14265.0	19236.0	33501.0	42.0	57.0
26	03/23/2012	16.0	5544.0	5833.0	11377.0	48.0	51.0
27	03/24/2012	7.0	5264.0	3865.0	9129.0	57.0	42.0
28	03/25/2012	49.0	31904.0	30062.0	61966.0	51.0	48.0
29	03/31/2012	15.0	2106.0	2468.0	4574.0	46.0	53.0
30	04/03/2012	9.0	1184.0	1237.0	2421.0	48.0	51.0
31	05/02/2012	30.0	2880.0	4833.0	7713.0	37.0	62.0
32	05/07/2012	11.0	1327.0	1890.0	3217.0	41.0	58.0
33	05/08/2012	21.0	6129.0	6038.0	12167.0	50.0	49.0
34	05/20/2012	13.0	1025.0	1306.0	2331.0	43.0	56.0
35	05/22/2012	52.0	15584.0	14239.0	29823.0	52.0	47.0
36	05/23/2012	86.0	104576.0	18743.0	123319.0	84.0	15.0
37	05/24/2012	34.0	41794.0	19271.0	61065.0	68.0	31.0
38	05/25/2012	5.0	1255.0	999.0	2254.0	55.0	44.0
39	05/26/2012	37.0	38685.0	27294.0	65979.0	58.0	41.0
40	06/02/2012	20.0	4486.0	4717.0	9203.0	48.0	51.0
41	06/03/2012	22.0	13122.0	8781.0	21903.0	59.0	40.0
42	06/04/2012	38.0	32150.0	25378.0	57528.0	55.0	44.0
43	06/05/2012	8.0	12702.0	10050.0	22752.0	55.0	44.0
44	06/06/2012	8.0	5433.0	3525.0	8958.0	60.0	39.0
45	06/07/2012	7.0	13217.0	8988.0	22205.0	59.0	40.0
46	07/08/2012	34.0	5660.0	5623.0	11283.0	50.0	49.0
47	07/08/2012	12.0	4528.0	6015.0	10543.0	42.0	57.0
48	07/26/2012	31.0	4796.0	6411.0	11207.0	42.0	57.0
49	07/27/2012	13.0	5516.0	6385.0	11901.0	46.0	53.0
50	08/07/2012	13.0	882.0	1571.0	2453.0	35.0	64.0
51	08/08/2012	44.0	17172.0	9804.0	26976.0	63.0	36.0
52	02/27/2013	4.0	756.0	1452.0	2208.0	34.0	65.0
53	03/03/2013	19.0	792.0	2509.0	3301.0	23.0	76.0
54	03/05/2013	11.0	541.0	1777.0	2318.0	23.0	76.0

55	03/05/2013	33.0	4994.0	16176.0	21170.0	23.0	76.0
56	03/06/2013	22.0	10726.0	26751.0	37477.0	28.0	71.0
57	03/07/2013	5.0	775.0	1819.0	2594.0	29.0	70.0
58	03/10/2013	6.0	680.0	2571.0	3251.0	20.0	79.0
59	03/11/2013	43.0	19107.0	40420.0	59527.0	32.0	67.0
60	03/21/2013	17.0	2580.0	5269.0	7849.0	32.0	67.0
61	03/23/2013	17.0	2151.0	7704.0	9855.0	21.0	78.0
62	03/26/2013	9.0	545.0	1474.0	2019.0	26.0	73.0
63	04/11/2013	8.0	369.0	1297.0	1666.0	22.0	77.0
64	04/16/2013	62.0	10340.0	28165.0	38505.0	26.0	73.0
65	04/17/2013	42.0	17144.0	42894.0	60038.0	28.0	71.0
66	04/18/2013	3.0	1767.0	4655.0	6422.0	27.0	72.0
67	04/18/2013	2.0	846.0	2178.0	3024.0	27.0	72.0
68	04/18/2013	9.0	1621.0	5532.0	7153.0	22.0	77.0
69	04/20/2013	27.0	6704.0	27501.0	34205.0	19.0	80.0
70	04/23/2013	86.0	63144.0	33894.0	97038.0	65.0	34.0
71	04/28/2013	14.0	5893.0	7407.0	13300.0	44.0	55.0
72	04/28/2013	2.0	10542.0	13364.0	23906.0	44.0	55.0
73	04/30/2013	111.0	82708.0	39233.0	121941.0	67.0	32.0
74	05/11/2013	19.0	3789.0	5916.0	9705.0	39.0	60.0
75	05/30/2013	10.0	1247.0	1772.0	3019.0	41.0	58.0
76	06/05/2013	177.0	138613.0	27276.0	165889.0	83.0	16.0
77	06/09/2013	1.0	1785.0	1950.0	3735.0	47.0	52.0
78	06/16/2013	30.0	11314.0	6350.0	17664.0	64.0	35.0
79	06/24/2013	9.0	4587.0	2955.0	7542.0	60.0	39.0
80	07/02/2013	13.0	3320.0	2578.0	5898.0	56.0	43.0
81	07/13/2013	24.0	5520.0	6316.0	11836.0	46.0	53.0
82	07/15/2013	9.0	2663.0	1162.0	3825.0	69.0	30.0
83	07/16/2013	17.0	5815.0	4509.0	10324.0	56.0	43.0
84	07/17/2013	26.0	14544.0	25462.0	40006.0	36.0	63.0
85	07/19/2013	34.0	13957.0	28596.0	42553.0	32.0	67.0
86	07/20/2013	26.0	16092.0	34908.0	51000.0	31.0	68.0
87	07/24/2013	13.0	2243.0	1888.0	4131.0	54.0	45.0
88	07/27/2013	22.0	5886.0	4163.0	10049.0	58.0	41.0
89	08/03/2013	20.0	3645.0	3731.0	7376.0	49.0	50.0
90	08/05/2013	19.0	12492.0	10070.0	22562.0	55.0	44.0
91	08/09/2013	81.0	26772.0	63930.0	90702.0	29.0	70.0
92	08/15/2013	28.0	3752.0	7636.0	11388.0	32.0	67.0
93	08/16/2013	102.0	60145.0	47130.0	107275.0	56.0	43.0
94	08/17/2013	0.0	1255.0	2297.0	3552.0	35.0	64.0
95	08/17/2013	85.0	47275.0	73771.0	121046.0	39.0	60.0
96	08/18/2013	5.0	1521.0	3582.0	5103.0	29.0	70.0
97	08/19/2013	36.0	13038.0	24494.0	37532.0	34.0	65.0
98	08/21/2013	12.0	1980.0	3709.0	5689.0	34.0	65.0
99	08/26/2013	29.0	2963.0	5490.0	8453.0	35.0	64.0
100	09/01/2013	41.0	9592.0	15806.0	25398.0	37.0	62.0
101	09/01/2013	3.0	3390.0	5620.0	9010.0	37.0	62.0
102	09/07/2013	23.0	4392.0	4692.0	9084.0	48.0	51.0
103	09/08/2013	8.0	4093.0	4949.0	9042.0	45.0	54.0
104	09/18/2013	16.0	3541.0	4793.0	8334.0	42.0	57.0
105	09/21/2013	14.0	2970.0	3809.0	6779.0	43.0	56.0
106	02/14/2014	25.0	11129.0	10822.0	21951.0	50.0	49.0
107	02/15/2014	7.0	4178.0	5397.0	9575.0	43.0	56.0
108	02/16/2014	0.0	1800.0	3838.0	5638.0	31.0	68.0
109	02/18/2014	12.0	2064.0	7026.0	9090.0	22.0	77.0
110	02/20/2014	29.0	7151.0	23927.0	31078.0	23.0	76.0
111	02/21/2014	51.0	19822.0	41477.0	61299.0	32.0	67.0
112	02/24/2014	16.0	3512.0	4329.0	7841.0	44.0	55.0
113	02/24/2014	1.0	2437.0	2558.0	4995.0	48.0	51.0

114	02/25/2014	67.0	23172.0	53565.0	76737.0	30.0	69.0
115	02/27/2014	16.0	9496.0	10192.0	19688.0	48.0	51.0
116	02/27/2014	12.0	11970.0	16225.0	28195.0	42.0	57.0
117	03/03/2014	0.0	1435.0	1441.0	2876.0	49.0	50.0
118	03/06/2014	3.0	2988.0	1869.0	4857.0	61.0	38.0
119	03/06/2014	41.0	17760.0	23829.0	41589.0	42.0	57.0
120	03/13/2014	45.0	9943.0	13565.0	23508.0	42.0	57.0
121	03/14/2014	11.0	13503.0	19938.0	33441.0	40.0	59.0
122	03/14/2014	12.0	2813.0	5276.0	8089.0	34.0	65.0
123	03/23/2014	11.0	1337.0	4027.0	5364.0	24.0	75.0
124	03/24/2014	6.0	1576.0	3013.0	4589.0	34.0	65.0
125	03/28/2014	8.0	1512.0	3724.0	5236.0	28.0	71.0
126	04/01/2014	33.0	1740.0	7044.0	8784.0	19.0	80.0
127	04/06/2014	61.0	13915.0	27351.0	41266.0	33.0	66.0
128	04/08/2014	18.0	4986.0	10385.0	15371.0	32.0	67.0
129	04/09/2014	18.0	6119.0	11750.0	17869.0	34.0	65.0
130	04/11/2014	14.0	3586.0	7585.0	11171.0	32.0	67.0
131	04/16/2014	9.0	565.0	2162.0	2727.0	20.0	79.0
132	04/17/2014	12.0	2271.0	4559.0	6830.0	33.0	66.0
133	04/17/2014	9.0	3767.0	7636.0	11403.0	33.0	66.0
134	04/18/2014	15.0	5828.0	12730.0	18558.0	31.0	68.0
135	04/19/2014	26.0	9058.0	27855.0	36913.0	24.0	75.0
136	04/19/2014	10.0	7815.0	21881.0	29696.0	26.0	73.0
137	04/25/2014	24.0	9048.0	15297.0	24345.0	37.0	62.0
138	04/26/2014	16.0	5427.0	8943.0	14370.0	37.0	62.0
139	04/27/2014	25.0	8430.0	20305.0	28735.0	29.0	70.0
140	04/28/2014	16.0	2748.0	8205.0	10953.0	25.0	74.0
141	04/28/2014	0.0	855.0	2634.0	3489.0	24.0	75.0
142	04/28/2014	27.0	8785.0	33864.0	42649.0	20.0	79.0
143	04/29/2014	6.0	1065.0	3447.0	4512.0	23.0	76.0
144	04/30/2014	29.0	20768.0	43623.0	64391.0	32.0	67.0
145	05/19/2014	14.0	2217.0	4677.0	6894.0	32.0	67.0
146	05/19/2014	27.0	4698.0	9150.0	13848.0	33.0	66.0
147	05/20/2014	12.0	4886.0	10631.0	15517.0	31.0	68.0
148	05/22/2014	63.0	10344.0	36648.0	46992.0	22.0	77.0
149	05/23/2014	1.0	1485.0	5040.0	6525.0	22.0	77.0
150	05/26/2014	4.0	2264.0	7894.0	10158.0	22.0	77.0
151	05/29/2014	8.0	3777.0	8673.0	12450.0	30.0	69.0
152	06/03/2014	11.0	2485.0	5683.0	8168.0	30.0	69.0
153	06/05/2014	75.0	18454.0	51224.0	69678.0	26.0	73.0
154	06/16/2014	7.0	2398.0	4088.0	6486.0	36.0	63.0
155	06/16/2014	24.0	9597.0	22539.0	32136.0	29.0	70.0
156	07/02/2014	68.0	11276.0	30561.0	41837.0	26.0	73.0
157	07/05/2014	33.0	14056.0	30023.0	44079.0	31.0	68.0
158	07/06/2014	20.0	3794.0	11113.0	14907.0	25.0	74.0
159	07/09/2014	10.0	1242.0	2347.0	3589.0	34.0	65.0
160	07/27/2014	1.0	1121.0	4235.0	5356.0	20.0	79.0
161	07/29/2014	334.0	176157.0	132096.0	308253.0	57.0	42.0
162	07/30/2014	77.0	47946.0	58704.0	106650.0	44.0	55.0
163	07/31/2014	114.0	69273.0	85587.0	154860.0	44.0	55.0
164	08/01/2014	4.0	1075.0	3839.0	4914.0	21.0	78.0
165	08/02/2014	2.0	2243.0	6196.0	8439.0	26.0	73.0
166	08/02/2014	13.0	12712.0	22143.0	34855.0	36.0	63.0
167	08/17/2014	13.0	2242.0	2618.0	4860.0	46.0	53.0
168	08/23/2014	6.0	2280.0	2598.0	4878.0	46.0	53.0
169	09/15/2014	14.0	2633.0	6322.0	8955.0	29.0	70.0
-	-	-	-	-	Average:	45	55

Figure Captions

Figure 1. Faga'alu watershed showing the Upper (undisturbed) and Lower (human-disturbed) subwatersheds. The Lower subwatershed drains areas between FG1 and FG3, and is further subdivided into the Lower_Quarry containing the quarry (between FG1 and FG2) and the Lower_Village containing the village areas (between FG2 and FG3). The Total watershed includes all subwatersheds draining to FG3. The Administrative watershed boundary for government jurisdiction is outlined by the dotted grey line. Blue pentagons in the Upper watershed show the location of abandoned water supply reservoirs (see Supplementary Material A for full description). Barometer locations at NSTP6 and TULA are shown in top-right.

Figure 2. Photos of the aggregate quarry in Faga'alu in 2012, 2013, and 2014. Pictures a-b show vegetation overgrowth during the period of study from 2012-2014, and the location of the groundwater diversion that was installed in 2012. Pictures c-d show that haul roads were covered in gravel in 2013. Photos: Messina

Figure 3. Time series of water discharge (Q) at FG1 and FG3, calculated from measured stage and the stage-discharge rating curves in a) 2012 b) 2013 and c) 2014.

Figure 4. Example of a storm event (02/14/2014). SSY at FG1 and FG3 calculated from SSC modeled from T, and SSY at FG2 from SSC samples collected by the Autosampler.

Figure 5. Boxplots of Suspended Sediment Concentration (SSC) from grab samples only (no Autosampler) at FG1, FG2, and FG3 during (a) non-stormflow and (b) stormflow.

Figure 6. Water Discharge (Q) versus suspended sediment concentration (SSC) measured from stream water samples at a) FG1, b) FG2, and c) FG3 during non-stormflow and stormflow periods. The box in b) highlights the samples with high SSC during low flows. Solid symbols indicate SSC samples where precipitation during the preceding 24 hours was 0 mm.

Figure 7. $sSSY_{EV}$ regression models for predictive storm metrics. Each point represents a different storm event. **=slopes and intercepts were statistically different ($p<0.01$), *=intercepts were statistically different ($p<0.01$).

Figure B.1. Stream cross-section at FG1

Figure B.2. Stream cross-section at FG3

Figure B.3. Stage-Discharge relationships for stream gaging site at FG3 for (a) the full range of observed stage and (b) the range of stages with AV measurements of Q. RMSE was 93 L/sec, or 32% of observed Q.

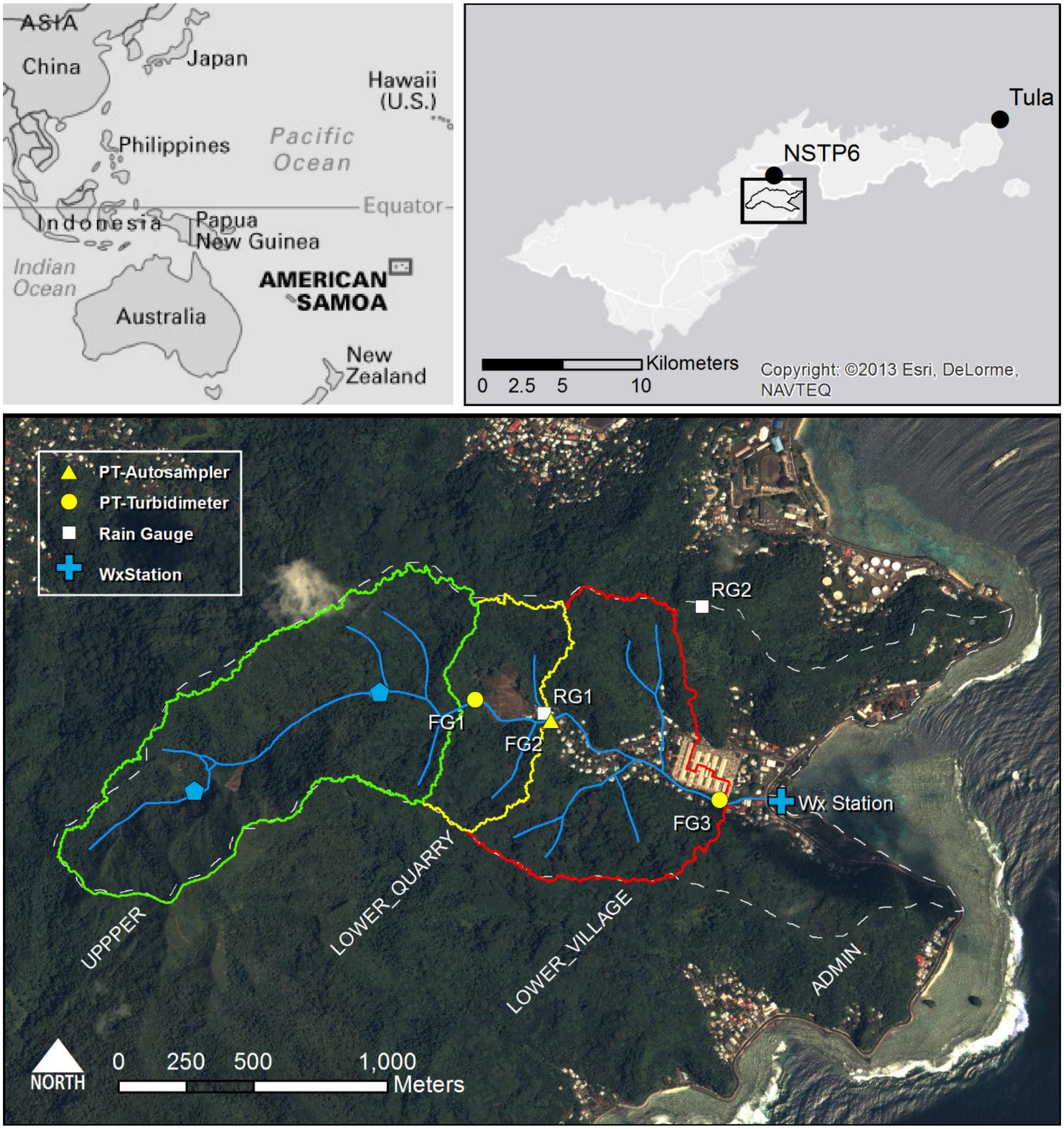
Figure B.4. Stage-Discharge relationships for stream gaging site at FG1 for (a) the full range of observed stage and (b) the range of stages with AV measurements of Q. RMSE was 31 L/sec, or 22% of observed Q. "Channel Top" refers to the point where the rectangular channel transitions to a sloped bank and cross-sectional area increases much more rapidly with stage. A power-law relationship is also displayed to illustrate the potential error that could result if inappropriate methods are used.

Figure C.1. Turbidity-Suspended Sediment Concentration relationships for a-b) the YSI turbidimeter deployed at FG3 (02/27/2012-05/23/2012) and the same YSI turbidimeter deployed at FG1 (06/13/2013-12/31/2014) (Same T-SSC relationship applied for TS deployed at FG1). c-d) OBS500 turbidimeter deployed at FG3 (03/11/2013-07/11/2013) and the same OBS500 turbidimeter deployed at FG3 (01/31/2014-03/04/2014).

Figure C.2. Synthetic Rating Curves for (a) OBS turbidimeter deployed at FG3 and (b) YSI deployed at FG1.

Figure D.1. Example of method for separating storms based on baseflow separation. Black line is hydrograph, grey line is baseflow calculated by R statistical package EcoHydRology. Storm periods are shaded in grey. Seven storm events are identified from March 3, 2013 to March 13, 2013.

Figure Captions



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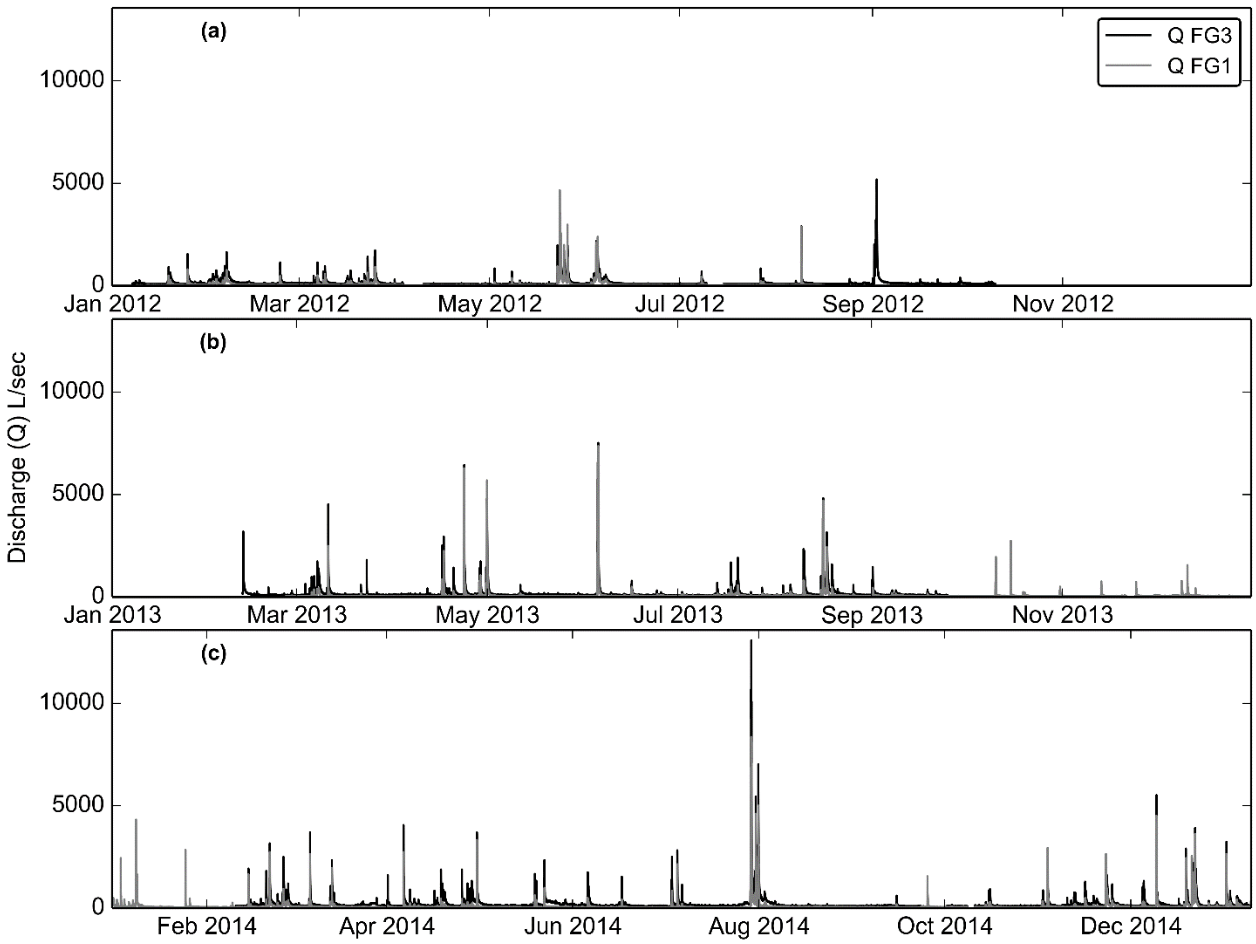

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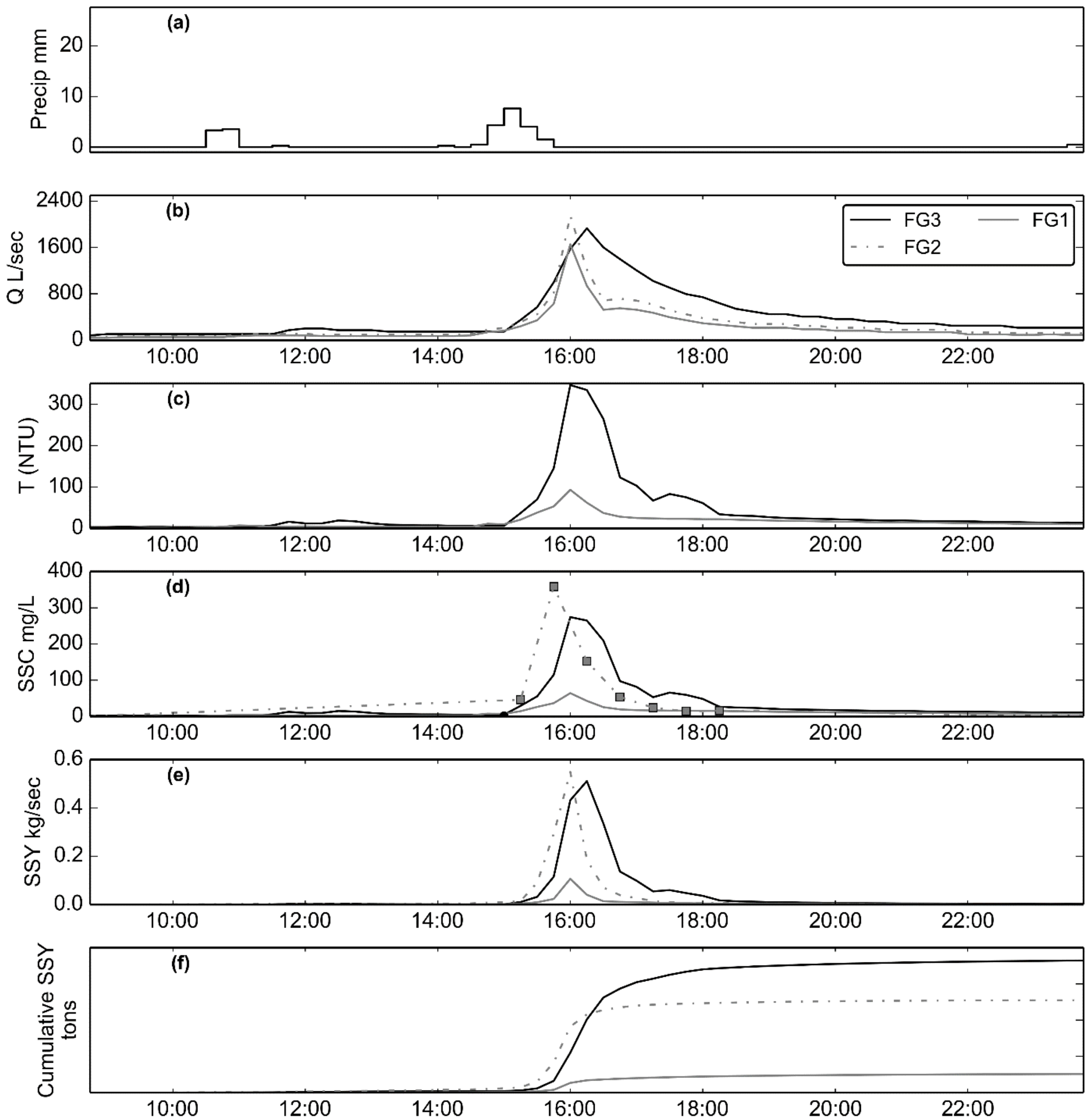

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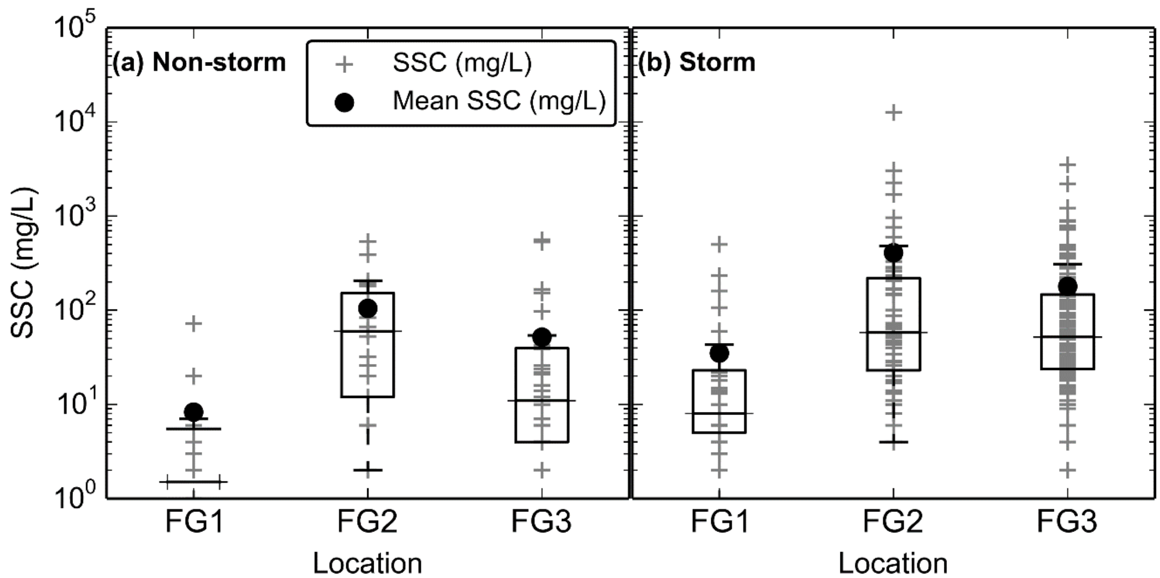

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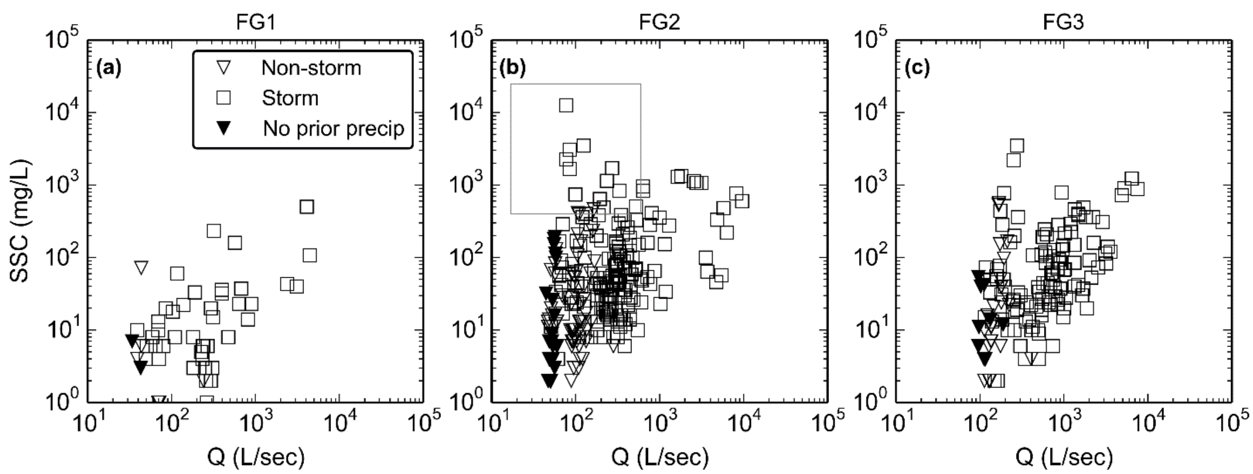

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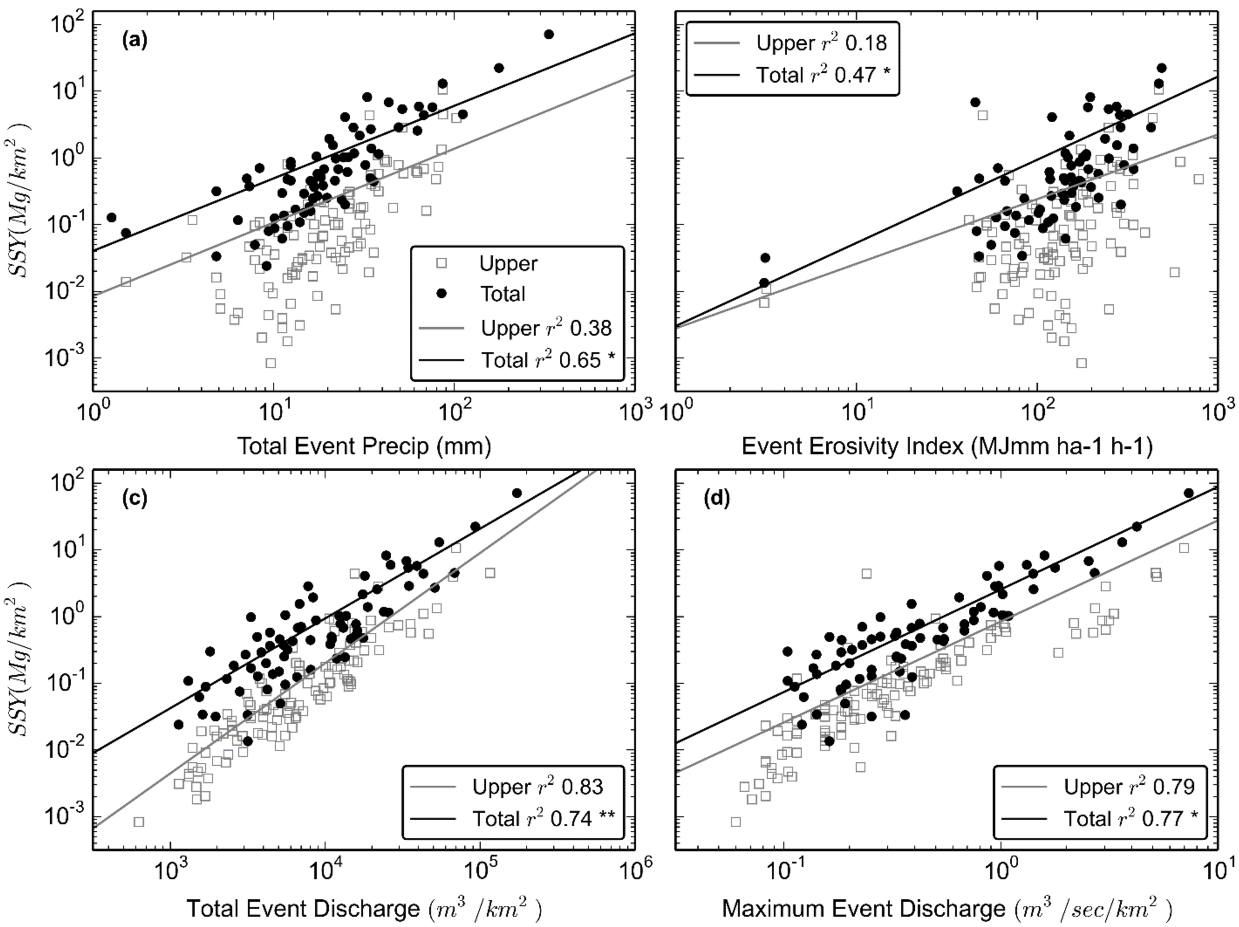

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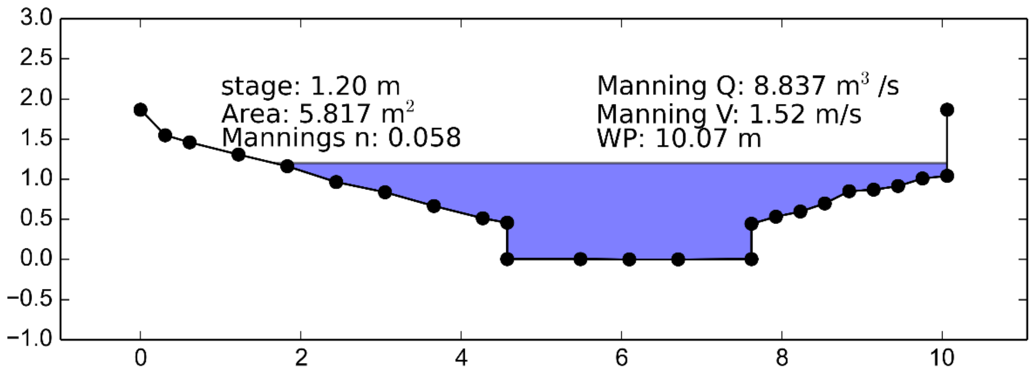

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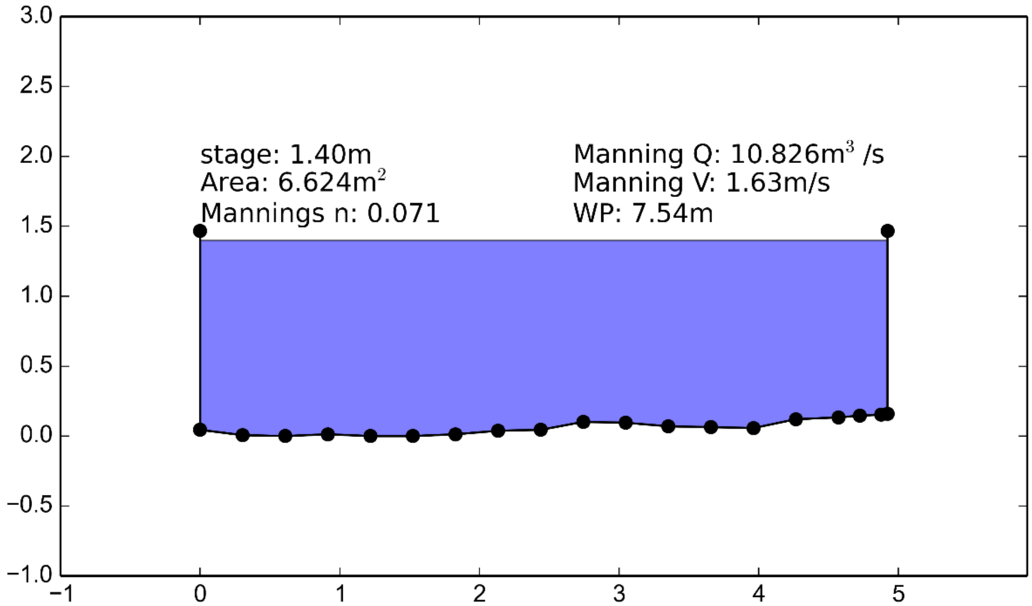
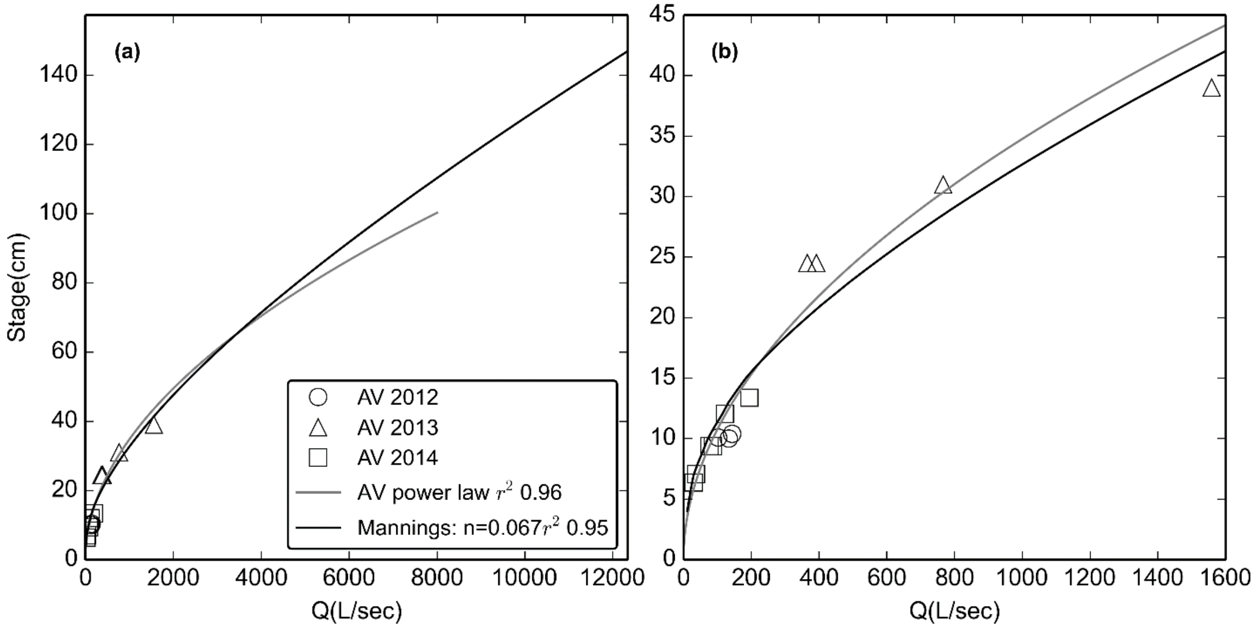


Figure B.2. Stream cross-section at FG3



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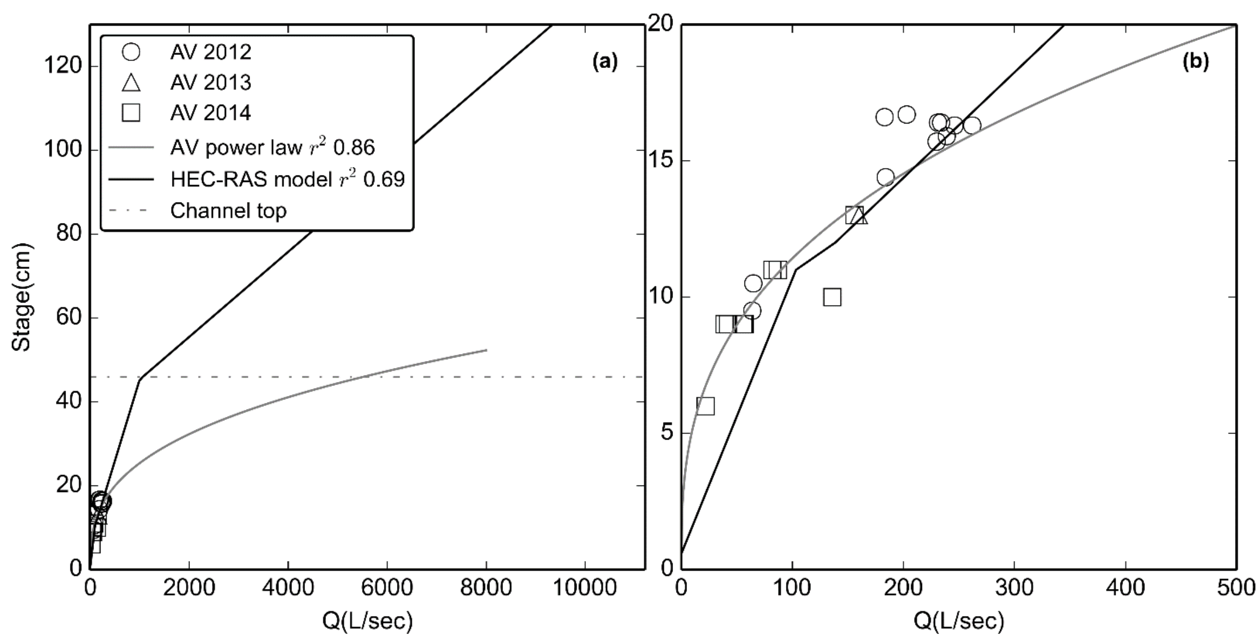

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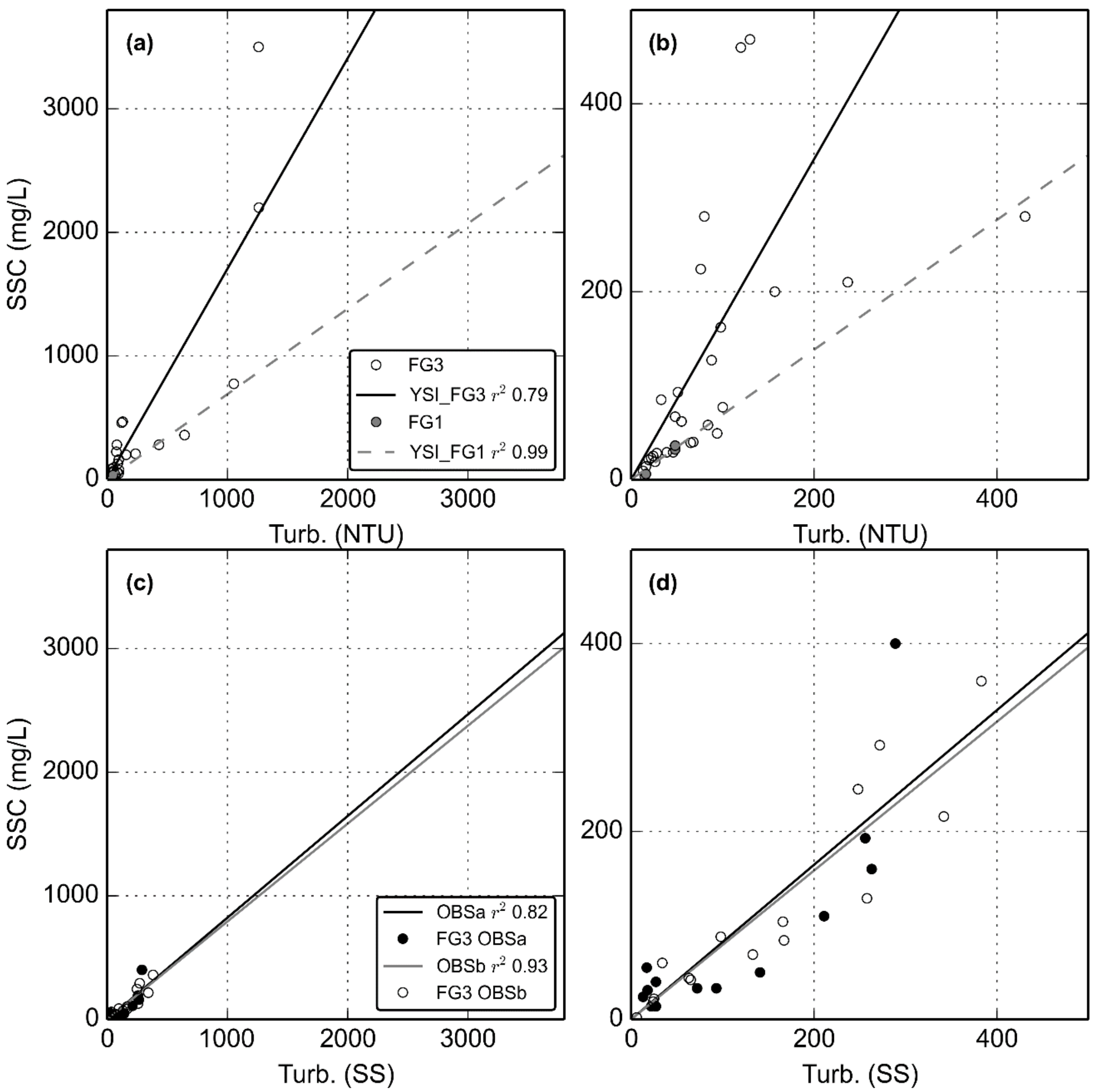

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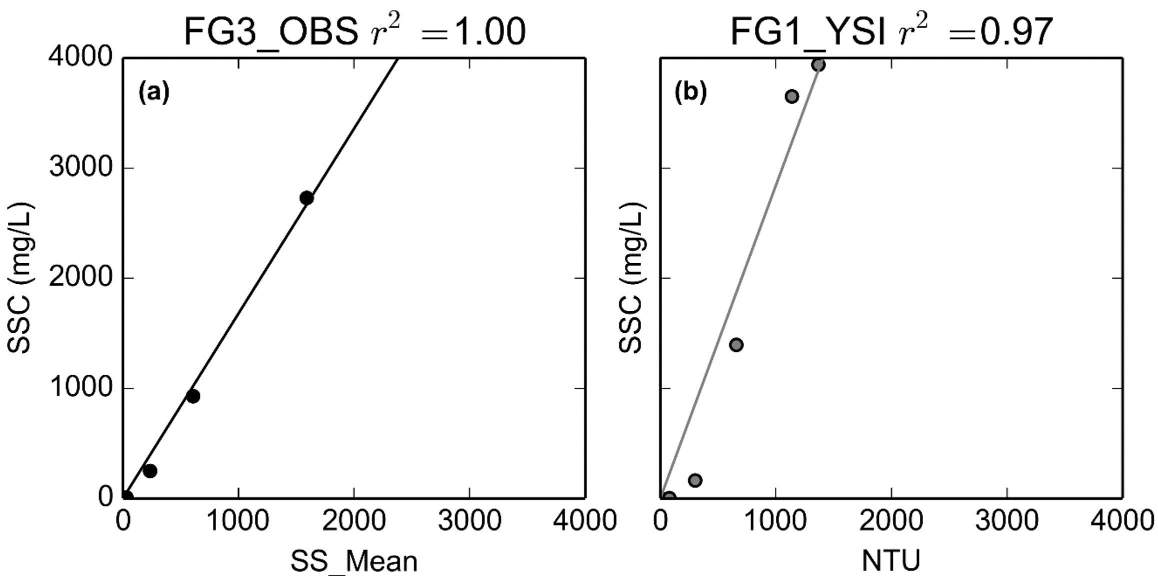

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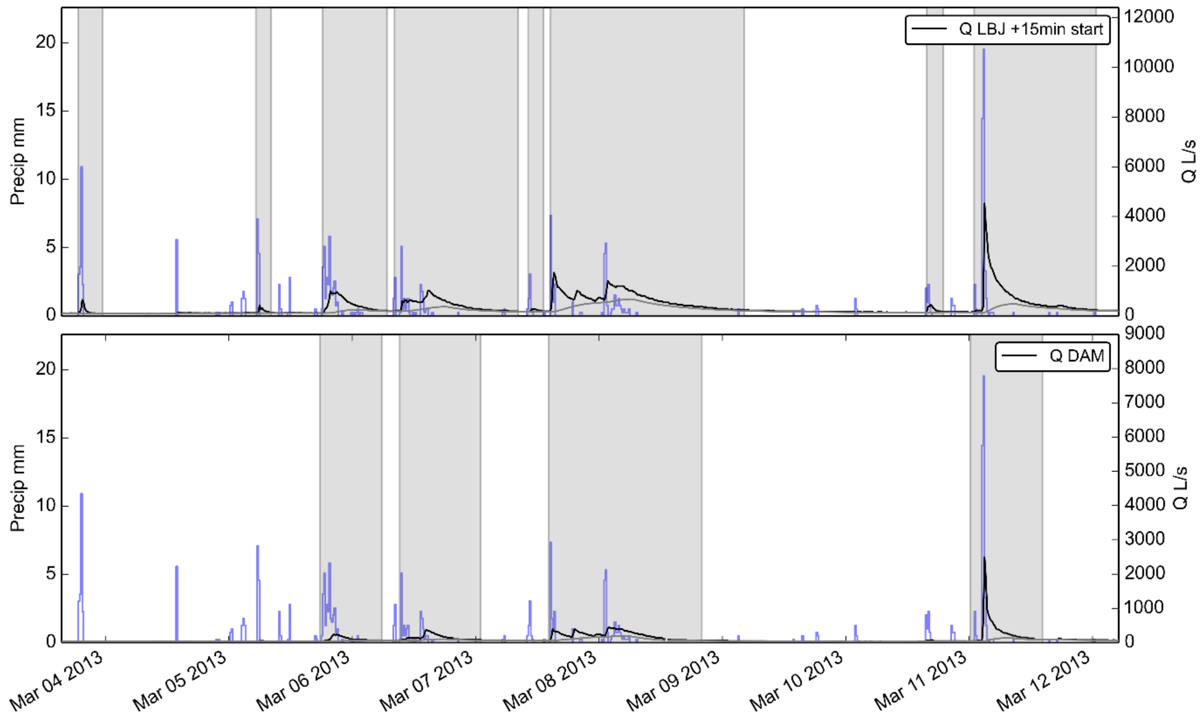

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