Expanding monitoring and modeling of land-based sources of pollution to priority coral reefs in American Samoa

Final Report

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Background

The project titled, "*Expanding monitoring and modeling of land-based sources of pollution to priority coral reefs in American Samoa*" was granted funding by the FY13 NOAA Coral Reef Conservation Program. The application for funding was made via American Samoa's Coral Reef Advisory Group (CRAG) by the San Diego State University Foundation. The project period was October 2013 to September 2015.

This report highlights the original objectives of the project and what was achieved during the project. Appendix A includes the manager-level summary of the methods and findings.

Introduction

Management of land-based sources of pollution to coral reefs requires knowledge of the sources and quantities of pollutants. Sedimentation and nutrient loading have been identified as key threats to coral reef health in the areas of Faga'alu bay and the Pala Lagoon (Nu'uuli Watershed), in American Samoa. To assess the severity of the problem and the potential for watershed and reef restoration in Faga'alu, the researchers have previously measured sediment flux from Faga'alu watershed and sediment accumulation rates on the reef. In August 2012, Faga'alu was selected by the US Coral Reef Task Force (CRTF) as a Priority Watershed Initiative, and a mitigation plan has been proposed for a key sediment source in the watershed, an open pit quarry that contributes nearly 75% of the sediment from the watershed (Messina, unpublished data). This mitigation plan could be implemented as early as 2013, so continued monitoring is important for establishing the baseline sediment and nutrient loading prior to mitigation, and for monitoring the effectiveness of mitigation activities. However, the sediment sources in Faga'alu are dominated by the open pit quarry, which makes Faga'alu a unique watershed on Tutuila. There is need for determining the sediment and nutrient impacts of human activities in a more "typical" watershed, one which is dominated by village settlements and includes relatively low population densities with small-scale agriculture and piggeries. The goal of this continuing project is to leverage our previous work in Faga'alu by continuing sediment and nutrient monitoring in Faga'alu before and possibly after the mitigation work, and to begin a similar measurement campaign in Nu'uuli, a similar sized, nearby priority watershed (2.5 km^2) that drains to coral reefs in the Pala Lagoon and has been identified by the ASEPA as impaired.

Objectives: Proposed and achieved

Specific objectives as originally stated in the MOU, and the achieved objectives by the end of the project were:

Proposed objective 1: A manager-level report detailing the major sources of sediment and nutrients in the Nu'uuli watershed and what management strategies will be most effective for reducing land-based sources of pollution to the priority coral reefs in the Pala Lagoon. The baseline data from Nu'uuli will also be used to set sediment mitigation goals in nearby Faga'alu, by providing context on what could be considered a "typical" watershed, and a realistically attainable goal for management activities.

Achieved objective 1: In collaboration with other NOAA researchers, we published a manager-level report detailing the major sources of sediment at Faga'alu (Holst-Rice et al, 2016). A similar version has been created for Nu'uuli watershed (see Appendix A).

Proposed objective 2: Development and calibration of a watershed model, N-SPECT, specifically tailored to management applications in the South Pacific high islands, and currently being developed by our partners on the Coral Reef Task Force.

Achieved objective 2: During the course of the investigation, it was concluded that N-SPECT-type modeling was inappropriate for the field situation given that sediment was generated from highly dynamics surfaces like the quarry, and from highly variable, non-agricultural sources in the village. We developed an alternative modeling strategy based on storm metrics, which was published in 2016 (Messina and Biggs, 2016). This strategy allowed for determination of the effectiveness of mitigation activities at the quarry.

Proposed objective 3: Build local technical capacity in watershed monitoring techniques and analysis amongst government agencies at AS-EPA, DMWR and community college students at ASCC.

Achieved objective 3: Monitoring at both Faga'alu and Nu'uuli were carried out with assistance from on-island students (Rocco Tinitali, Valentine Vaeoso), CRAG (Meagan Curtis) and ASCC (Jameson Newtson). The collaboration has been extended with follow-up funding from the National Fish and Wildlife Foundation (NFWF) through December 2016, including training of AS-EPA staff in data downloading and analysis.

Proposed objective 4: Contributions to scientific knowledge on sediment and nutrient production processes, sediment and nutrient management strategies, and linkages between land use, sediment, nutrients and coral reef ecosystems will be generated and published in scientific journals.

Achieved objective 4: The results of the monitoring were presented at academic conferences, reports, journal articles, and components of two doctoral and master's theses. Some components of the following include results from prior and continuing projects, but all contain results from the currently funded project:

Peer-reviewed reports:

Holst-Rice, S., Messina, A. T., Biggs, T. W., Vargas-Angel, B., & Whitall, D. 2016. *Baseline Assessment of Faga'alu Watershed: A Ridge to Reef Assessment in Support of Sediment Reduction Activities and Future Evaluation of their Success*. Silver Spring, MD. doi:10.7289/V5BK19C3

Conference proceedings:

Messina, A., Biggs, T., 2015, Contributions of human activities to suspended-sediment yield during storm events from a steep, small, tropical watershed, American Samoa, Poster Presentation, U.S. Coral Reef Task Force Meeting, Puerto Rico.

Messina, A. T., & Biggs, T. W. 2014. Contributions of human activities to suspended-sediment yield during storm events from a steep, small, tropical watershed, American Samoa. In *AGU Fall Meeting Abstracts* (Vol. 1, p. 3487).

Peer-reviewed publications:

Messina, A. M., & Biggs, T. W. 2016. Contributions of human activities to suspended sediment yield during storm events from a small, steep, tropical watershed. *Journal of Hydrology*, *538*, 726–742. doi:10.1016/j.jhydrol.2016.03.053

Messina, A.M., and Biggs, T.W., in prep. Mitigation of sediment load to a coral reef: Documentation of successful sediment control.

Theses and dissertations:

Chapter 1 in Messina, A.T., 2016. *Terrigenous Sediment Dynamics in a Small, Tropical Fringing-Reef Embayment, American Samoa*. PhD Dissertation for San Diego State University/UC Santa Barbara Joint-Doctoral Program, Department of Geography.

McCormick, G, in prep. *Nutrient concentrations and its relationship to land use in American Samoa during baseflow and storm conditions*. MS Watershed Science, San Diego State University.

Additional achieved objective: During the project period, significant mitigation efforts were undertaken at the quarry in Faga'alu watershed, including flow diversion, road stabilization, and construction of sediment retention ponds (see Appendix A). The current project allowed for collection of turbidity and streamflow data after the restoration, which then provided a test of the effectiveness of the mitigation activities at reducing sediment loading during storm events. This is a significant additional achievement that is being continued with additional funding from NFWF.

Appendix A. Manager-level report of findings at Faga’alu and Nu’uli watersheds during the project period

Objective

The objective of this project was to take simultaneous measurements of stream discharge, suspended sediment concentration, and nutrient concentrations in both Faga’alu and Nu’uli watersheds to quantify the loading of these pollutants during storm and inter-storm periods from the natural and human-impacted parts of the watersheds. This project continued monitoring in Faga’alu that was begun in January 2012, and replicated the same methods in Nu’uli with the end goal of quantifying the human impact on water quality and developing a model of pollutant loading to coral reefs that can be applied in the Pacific high islands.

Methodology

Two tipping bucket rain gauges were installed in both Faga’alu and Nu’uli watershed to record rainfall over the course of 2 years. Pressure sensors to measure stream water level ("stage") were installed at two sites in each watershed (F1, F3, N1 and N2 shown in Figure A1). Water level was monitored using a head of pressure, which was converted to streamflow via Manning’s equation and by direct comparison with actual streamflow measurements using AS-EPA’s Marsh McBirney flow meter. Two nearby meteorological stations (located at the airport and at Faga’alu) were used to correct for atmospheric pressure. Stream water samples were collected during storm and inter-storm periods by both manual grab samples in wide-mouth 250ml bottles and by an ISCO autosampler when manual sampling is not possible. The stream samples were filtered and analyzed for sediment concentration (total suspended solids (TSS)) at the DMWR laboratory using gravimetric methods. During the 2013 campaign, filters with a nominal pore size of 1.5 um were used for filtration. This is non-standard, and in 2014, both 1.5 um and the more commonly used 0.7 um filters were used in order to determine the effect of filtering with 0.7 vs 1.5 um filters. Filtered samples were frozen until analysis.

Turbidimeters were installed at the same locations as the pressure sensors (F1, F3, N1 and N2 in Figure A1) to develop a turbidity vs TSS relationship which can be used to convert continuous turbidity monitoring to continuous sediment concentration. A sub-sample was refrigerated and sent to a lab at SDSU to be analyzed for colorimetric analysis of nitrate and phosphate. A discharge-concentration relationship for sediments and nutrients were determined and used to quantify sediment and nutrient flux based on continuous stream discharge data. Sediment traps installed on the reef during our previous work in Faga’alu will collect sediment settling on the reef and these were collected on a monthly basis, in addition to opportunistic grab samples from sediment deposits near the sediment traps.

Monitoring at Faga’alu extended that of a previous Territorial Grant (October 2012-Oct 2013). The monitoring period for the current grant was October 2013 to May 2015, which allowed for collection of additional data that was critical for the establishment of a baseline and for quantifying the success of mitigation activities.

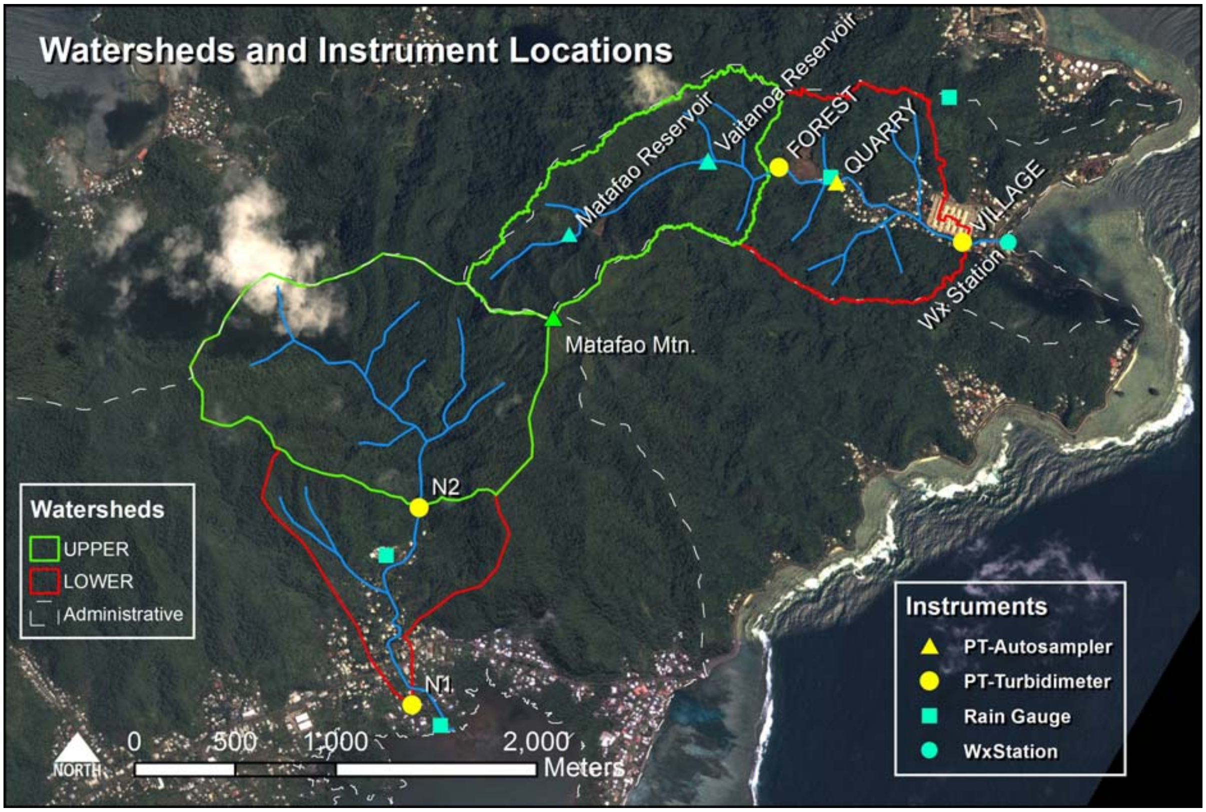

Figure A1. Faga'alu and Nu'uli watersheds. At Faga'alu, FOREST is F1, QUARRY is F2, and VILLAGE is F3. At Nu'uli, N2 is the forested watersheds, and N1 is the village watershed. Green lines outline the Upper watersheds and red lines outline the Lower subwatersheds. The grey dotted lines outline the rest of the administrative watersheds (Faga'alu and Nu'uli/Pala respectively)

Results

Nutrients: Impact of filter size

Nitrate results for samples filtered with 1.5 um filters correlated closely with nitrate results for the same samples filtered with 0.7 um filters, particularly for higher concentrations (>0.3 mg/L), with a mean absolute error of 0.045 mg/L, and relative mean absolute error of 39% (Figure A2). NO3 concentrations were generally lower after filtering with the 1.5 um filter, possibly because organisms that assimilate NO3 were present in the water after filtering with 1.5 um. Overall, the results suggest that NO3 results from the two filters are broadly comparable, especially for high concentrations, but that the results from the 1.5 um filters are likely lower than would be obtained from 0.7 um filters.

Phosphate results for samples filtered with 1.5 um filters were within 12% of the results for the 0.7 um filter with one exception (Figure A3). The mean absolute error with the outlier is 12%, and 5% without the outlier. We conclude that PO4 obtained from the two filters are comparable.

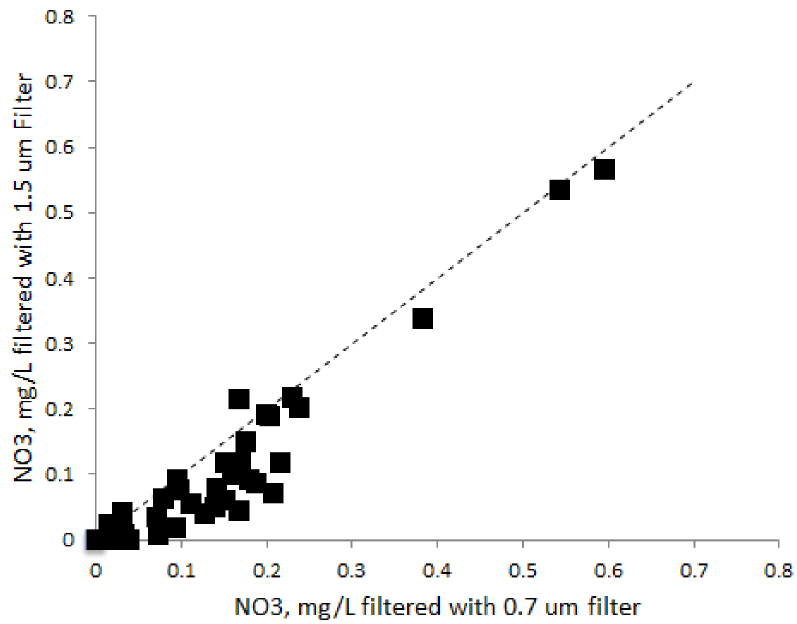

Figure A2. Relationship between NO3 in water filtered with 0.7 um and the same sample filtered with 1.5 um pore size filters. The dashed line is the 1:1 line.

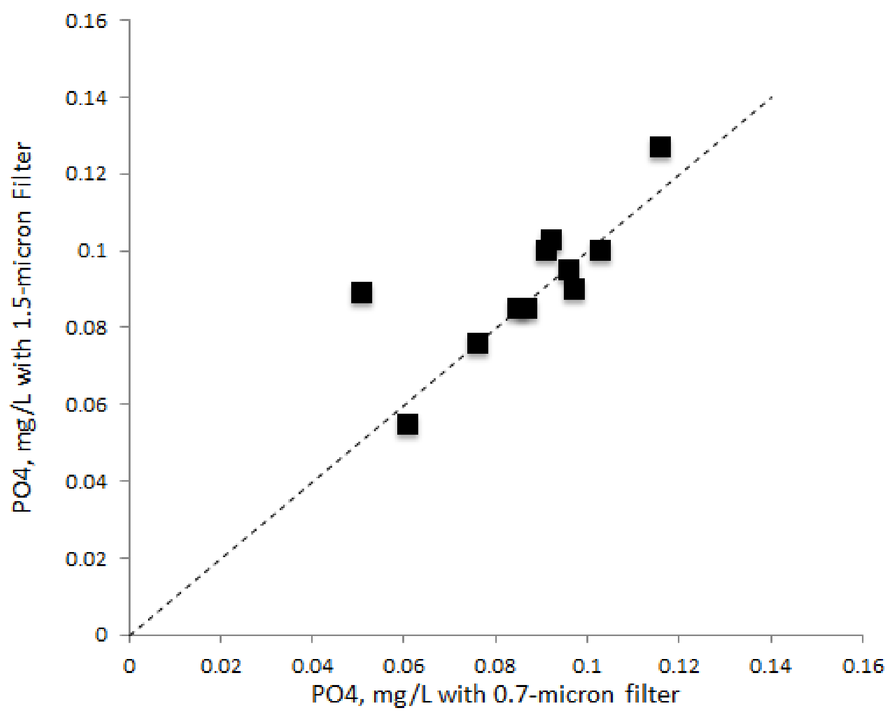

Figure A3. Relationship between PO4 in water filtered with 0.7 um and the same sample filtered with 1.5 um pore size filters. The dashed line is the 1:1 line.

Faga'alu

Watershed characteristics and mitigation activities

Land use at Faga'alu was characterized for each of the watersheds that drain to each of the monitored locations (Table 1).

Table A1. Land use in Faga'alu subwatersheds as percentages of each subwatershed and the total watershed draining to F3. Land cover data from NOAA Ocean Service and Coastal Services Center, 2010). Source: Messina and Biggs (2016)

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[b]	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.

The monitoring period overlapped with mitigation activities at the quarry (Figure A4-A5), which allowed rigorous determination of the impact of mitigation activities on sediment concentrations and loads. Sediment mitigation activities at the quarry began in June 2012 and continued until December 2014 with the installation of settling ponds (see Holst-Rice, et al. 2016 for a full description of mitigation activities).

Figure A4. Photos of the quarry in Faga'alu in 2012 (a,c), 2013(d), and 2014 (b). A-b show vegetation overgrowth between 2012 and 2014, and the location of the groundwater diversion that was installed in 2012. Pictures c-d show haul roads that were covered in gravel in 2013. Photos: Messina.


Figure A5. Photograph before (left) and after (right) installation of settling ponds.

Suspended sediment and turbidity

Samples collected prior to the installation of the sediment ponds allowed for assessment of the pre-mitigation baseline, which included 42 storms total, and 14 storms during the current project period (Table A2). Monitoring continued after the installation of sediment retention ponds, from October 1, 2014 to January 9, 2015. Measurements of turbidity and discharge are being made at the forest and quarry under a different grant from January 2015 through December 2016.

The suspended sediment yield during storm events (SSY_{EV}) post-mitigation (Figure A6) was similar to the SSY_{EV} for the undisturbed, forested background, indicating that the restoration activities in the watershed returning to a pre-disturbance level of suspended sediment load, except for the largest events.

Table A2. Event-wise suspended sediment yield (SSYEV) from subwatersheds in Faga'alu for events with data at both F1 and F3. Source: Messina and Biggs, 2016.

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

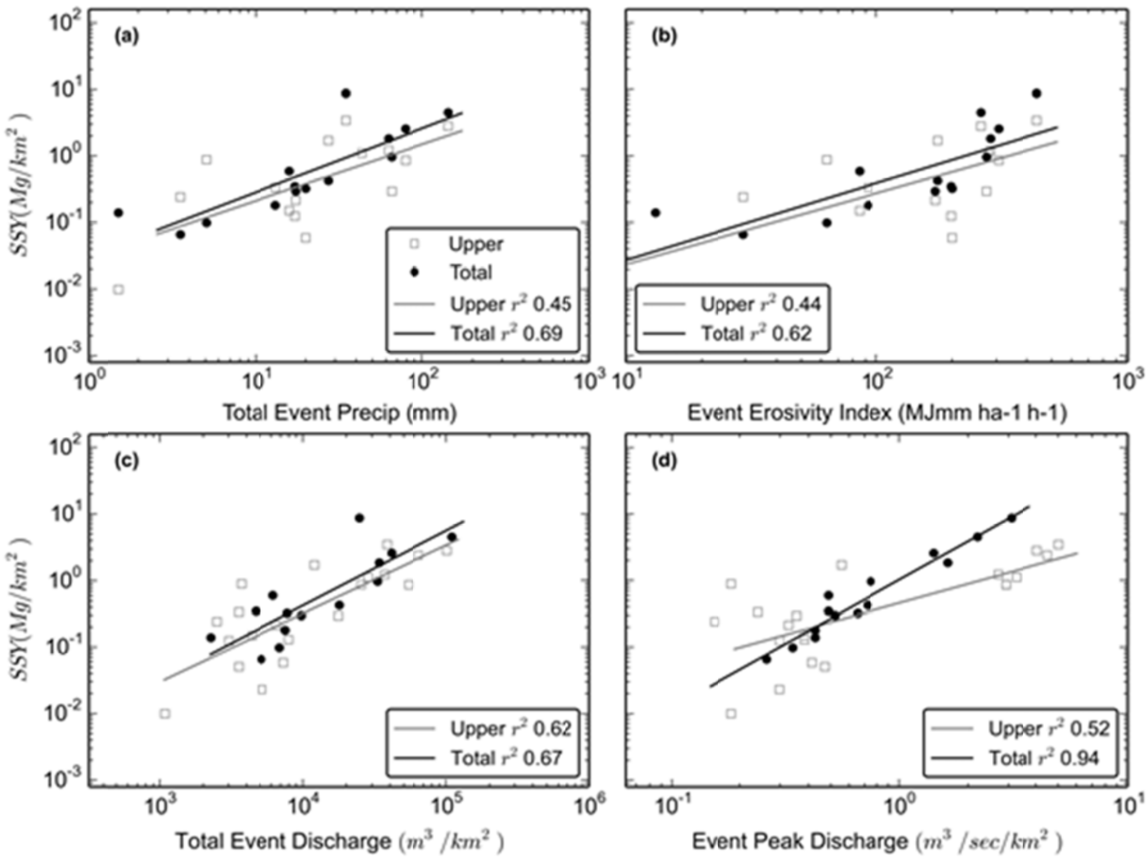

Figure A6. Relationship between storm metrics and SSY_{EV} for the post-mitigation period. SSY_{EV} at the village ("Total", corresponds to point F3, labelled "Village in Figure A1) was similar to the SSY_{EV} from the forest ("Upper", F1, labelled "Forest" in Figure A1).

Nutrient concentrations

A total of 5 storms were sampled at Faga'alu during the study period (Table A3). Between 2 and 5 samples were collected during each storm at both the forest and village sites (Figure A1). All five storms have results for nitrate, and 2 storms have results for phosphate due to low concentrations and laboratory instrument malfunction.

The volume-weighted mean (VWM) concentration of nitrate at the village was higher than at the forest for all but one event (Figure A7). In one event, the VWM concentration at the village was ~6x the concentration in the forest. By contrast, concentrations of phosphate were the same or lower at the village compared with the forest (Figure A7). This pattern, with nitrate showing larger impacts than phosphate from human activities, is also observed in an island-wide survey (McCormick, 2016).

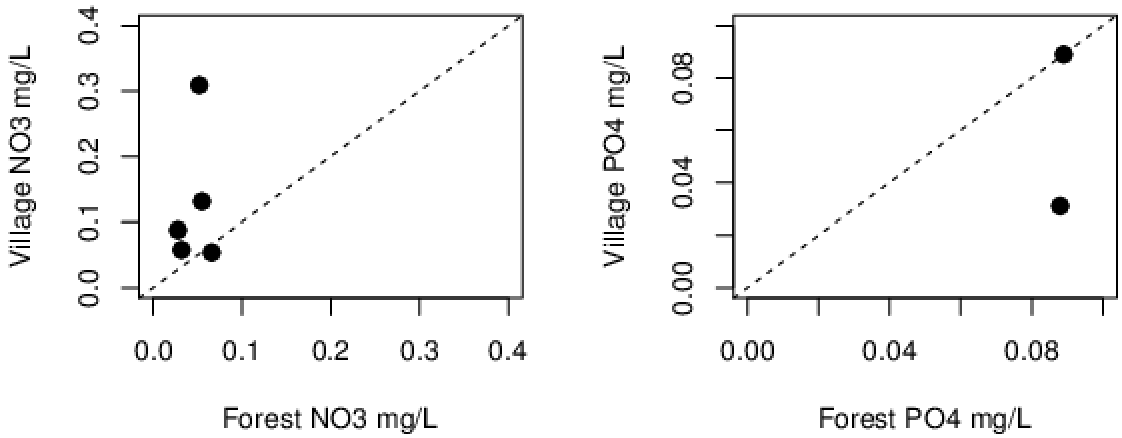

Figure A7. Volume-weighted mean concentration of nitrate and phosphate at the forest and village in Faga'alu during storm events. Dashed line is the 1:1 line.

NO3 concentrations were relatively invariant (~0.5 mg/L) for flows above 0.5 m3/s/km2 at the forest location, while concentrations at the village were consistently higher than those at the forest during events (~0.05 - 0.2 mg/L, with one outlier at 0.5 mg/L) (Figure A8). Concentrations during lower discharges were highly variable. By contrast, PO4 concentrations were consistently lower at the village site compared with the forest site for higher discharge (>0.25 m3/s/km2). The low PO4 concentrations downstream of the quarry may be due to sorption of PO4 onto sediment from the quarry. Insufficient data on total P concentrations are available at the time of this report to draw any conclusions about total P loading during storm events.

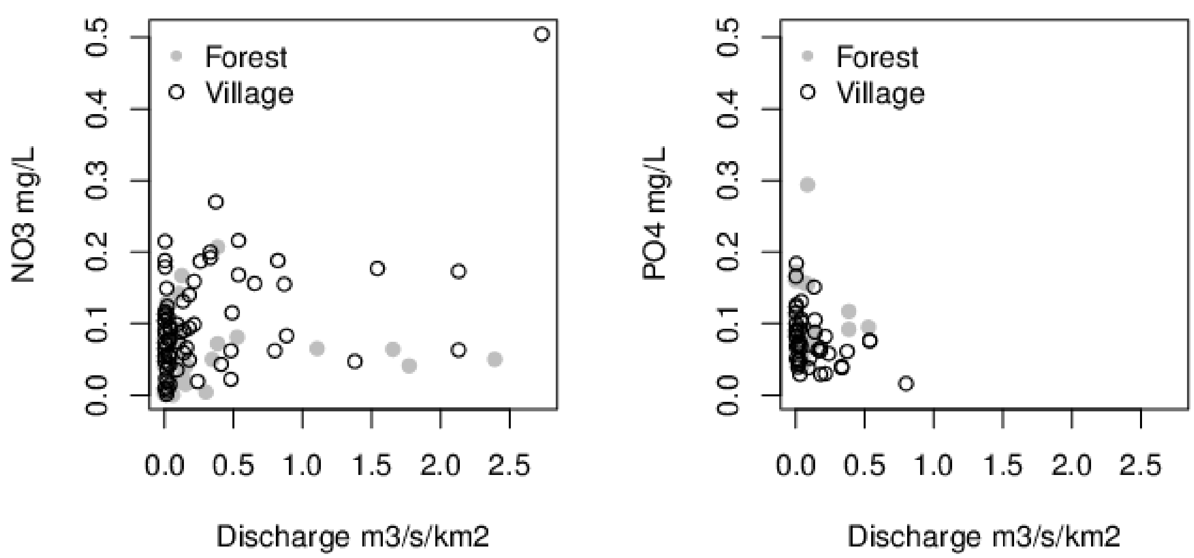

Figure A8. Concentration versus discharge for all storm samples at Faga'alu.

For individual storms, the concentration-discharge relationships showed a wide range of behavior at the different sampling locations (Figures A9-A13). NO3 concentrations were highest on the falling limb of the hydrograph for two storms, which suggests a subsurface flowpath, perhaps through leaky septic systems. One storm had the highest NO3 concentrations before the storm, suggesting high baseflow concentrations. Two storms had high concentrations at local peaks in the hydrograph. Overall, there is more evidence for subsurface generation of nitrate than wash-off of material accumulated on the surface between storms. This suggests that mitigation of groundwater contamination is a critical requirement for mitigating nitrate concentrations. The main caveat to this conclusion is that few storms had sufficient samples to adequately characterize the rising limb of the hydrograph, which would indicate an overland flow source but is very brief and difficult to capture.

Table A3. Inventory of nutrient analyses for storm samples at Faga'alu and Nu'uli. Filter indicates the mean pore diameter of the filters used in preparation of the sample. In 2014, several samples were filtered using both 0.7 um and 1.2 um filters.

Date	Filter	N samples for NO3		N samples for PO4	
		Forest	Village	Forest	Village
Faga'alu					
2013-03-06	1.5	4	7	4	7
2013-04-16	1.5	3	3	3	3
2013-04-23	1.5	4	5	0	0
2013-04-30	1.5	4	6	0	0
2015-06-05	1.5	2	4	0	0
Nu'uli					
2014-02-14	1.5 and 0.7	1	1	1	1
2014-02-26	1.5 and 0.7	1	2	1	2
2013-03-06	1.5	2	3	2	3
2013-03-23	1.5	2	4	2	4
2013-04-17	1.5	1	1	1	1
2013-06-05	1.5	3	3	0	0

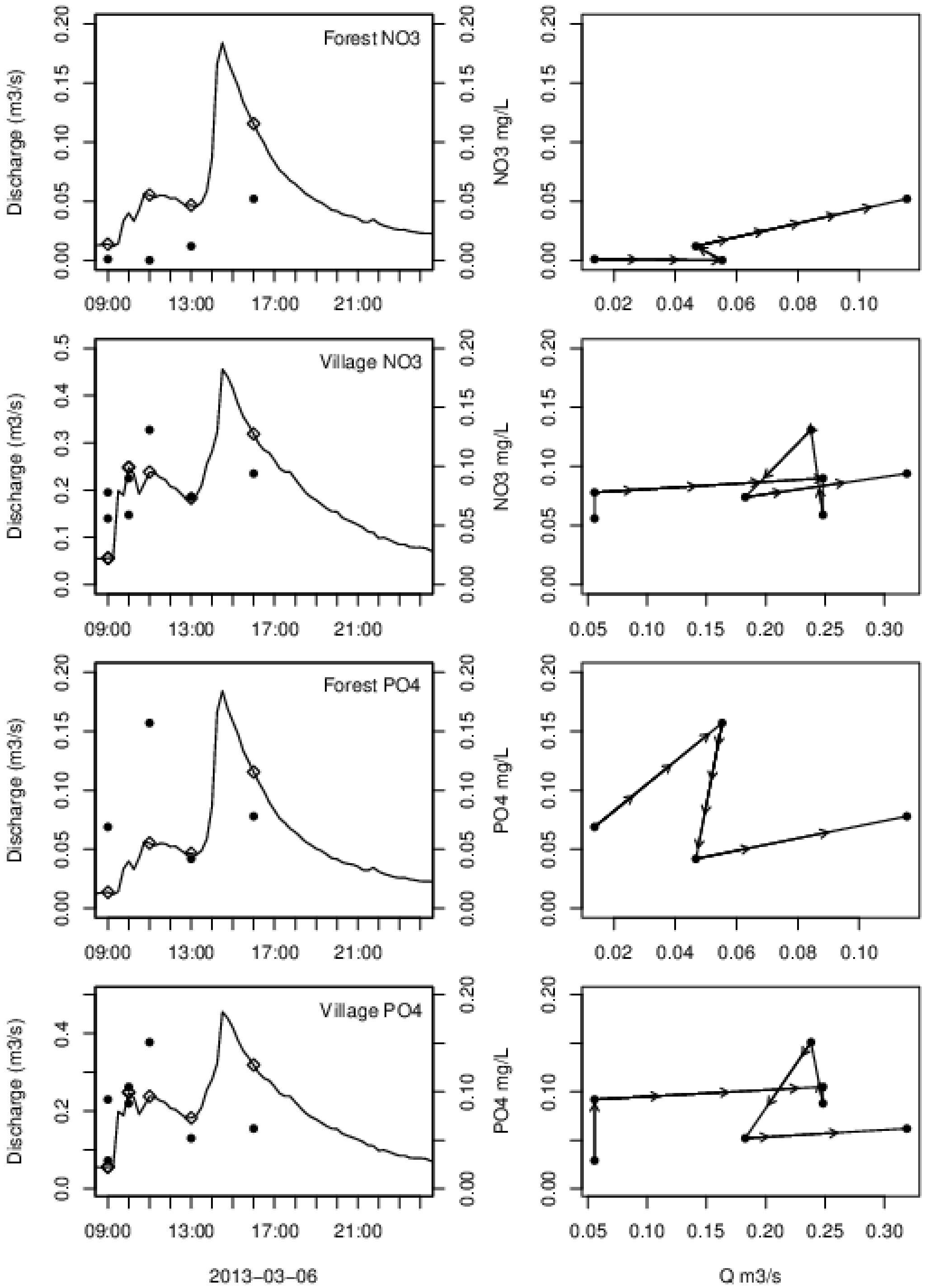

Figure A9. Time-series of discharge and concentration (left) and discharge-concentration relationships at Faga'alu for the storm on 2013-03-06 for nitrate and phosphate in the forest and village sites. Hollow diamonds in the left panels indicate the discharge at the sampled times, and black dots indicate concentrations.

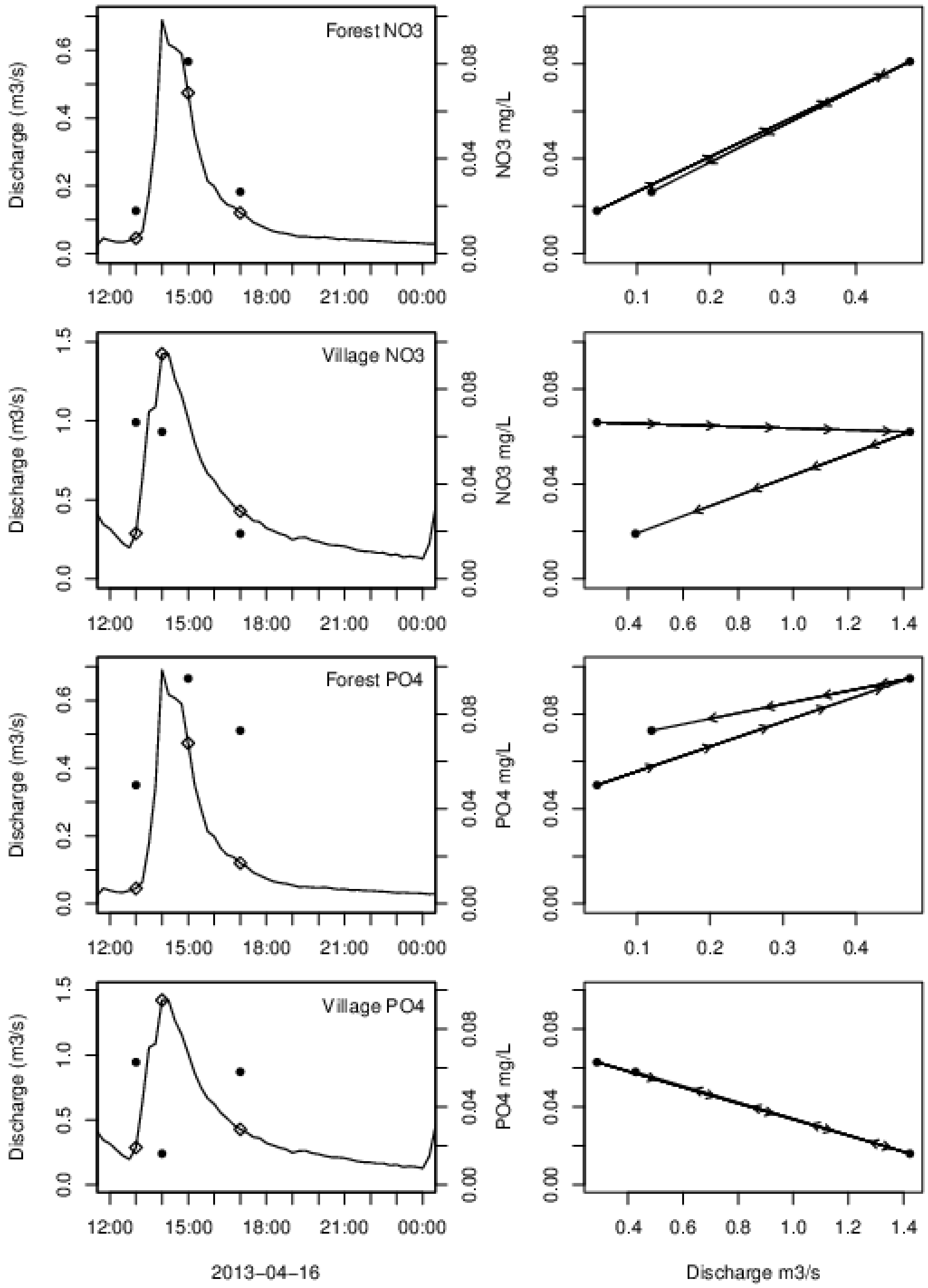

Figure A10. Time-series of discharge and concentration (left) and discharge-concentration relationships at Faga'alu for the storm on 2013-04-16 for nitrate and phosphate in the forest and village sites. Hollow diamonds in the left panels indicate the discharge at the sampled times, and black dots indicate concentrations.

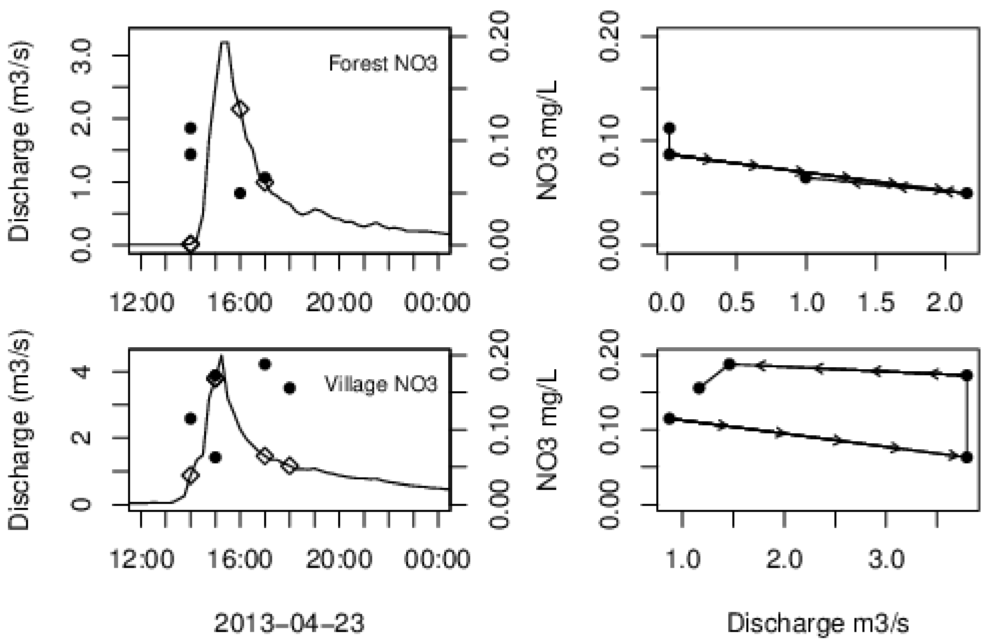

Figure A11. Time-series of discharge and concentration (left) and discharge-concentration relationships at Faga'alu for the storm on 2013-04-23 for nitrate in the forest and village sites. Hollow diamonds in the left panels indicate the discharge at the sampled times, and black dots indicate NO3 concentrations.

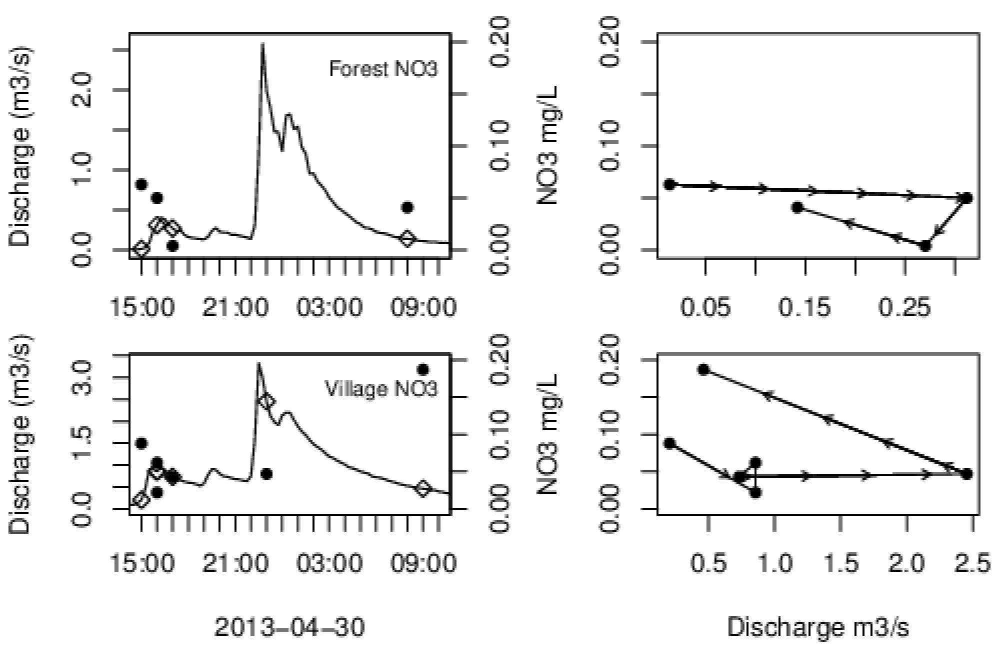

Figure A12. Time-series of discharge and concentration (left) and discharge-concentration relationships at Faga'alu for the storm on 2013-04-30 for nitrate in the forest and village sites. Hollow diamonds in the left panels indicate the discharge at the sampled times, and black dots indicate NO3 concentrations.

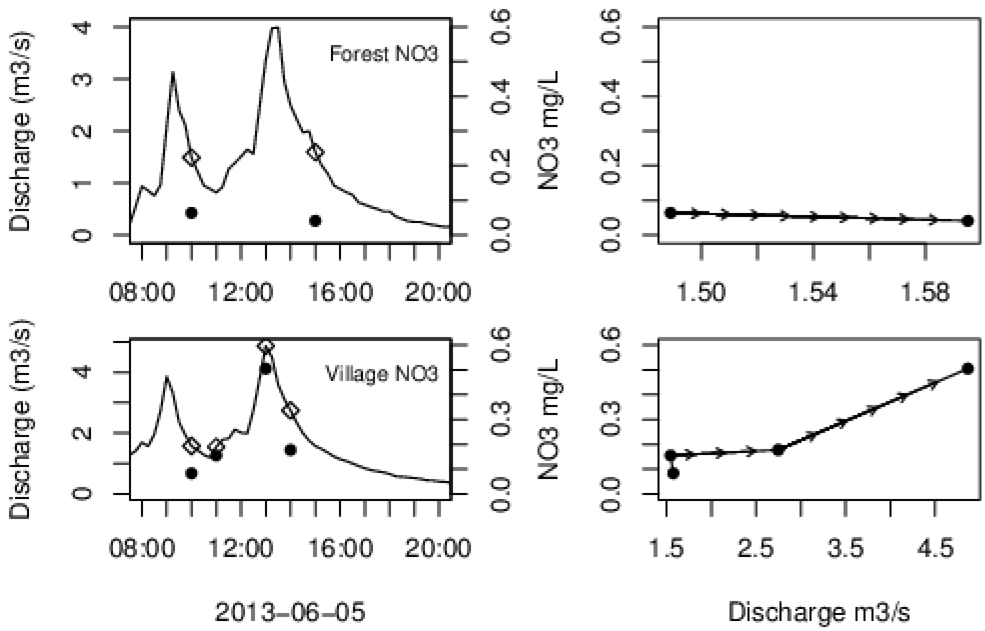

Figure A13. Time-series of discharge and concentration (left) and discharge-concentration relationships at Faga'alu for the storm on 2013-04-30 for nitrate in the forest and village sites. Hollow diamonds in the left panels indicate the discharge at the sampled times, and black dots indicate NO3 concentrations.

Nu'uli

Nu'uli watershed has a similar drainage area (2.1 km^2) compared with Faga'alu (1.8 km^2) but has a lower percentage of the watershed in high-intensity development (1.2% Nu'uuli vs 3.2% Faga'alu) (Table A3).

Table A3. Land cover percentages in the Nu'uli watershed. Upper corresponds to the watershed upstream of N2, and Total to the watershed upstream of N1.

	Cumulative Area		Subwatershed Area		Land cover as % subwatershed area [a]							
Watershed	km^2	%	km^2	%	B	HI	DOS	GA	F	S	Disturbed	Undisturbed
Nuuuli Upper	1.5	70	1.49	70	0.0	0.0	0.0	0.0	95	5.2	0.0	100
Nuuuli Lower	2.1	100	0.65	30	0.2	2.0	0.8	0.1	93	3.7	3.0	97
Nuuuli Total	2.1	100	2.14	100	0.1	1.2	0.4	0.0	94	4.3	1.8	98

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

Streamflow and turbidity

Streamflow data were collected in Nu'uli in varying intervals from March, 4, 2013 to December 29, 2014 (Figure A14). Turbidity data are available from February 10, 2014 to August 9, 2014 (N1) and February 7, 2014 to December 22, 2014. Over the period of record, there is a drift to increasing turbidity at both N1 and N2, which may reflect instrument drift over time. The turbidimeter at N2 likely malfunctioned in June 2014, when extremely low turbidity values were recorded. Here we focus on a period of high-quality measurements at both N1 and N2 from February 2014 to May 2014 (Figure A15).

A boxplot of turbidity during stormflow and baseflow at Nu'uli indicate no significant difference between the upstream (N2) and downstream (N1) locations during stormflow, and higher concentrations downstream at N1 compared with upstream (N2) during baseflow (Figure A16). The village at Nu'uli is not having a significant impact on turbidity during storm events, but that there is a small but measurable difference in turbidity during baseflow. This suggests that the village is not a source of sediment above the background rates during storms, and that no significant management efforts needs to be planned to mitigated turbidity or sediments during storms. The slightly higher turbidity during baseflow is small enough that it could be due in part to measurement error. If the difference in turbidity during baseflow is accurate, that suggests there are subsurface or in-stream generated sources of turbidity, such as leaky septic systems, discharge of household waste into the stream, or in-stream debris that is generating additional turbidity.

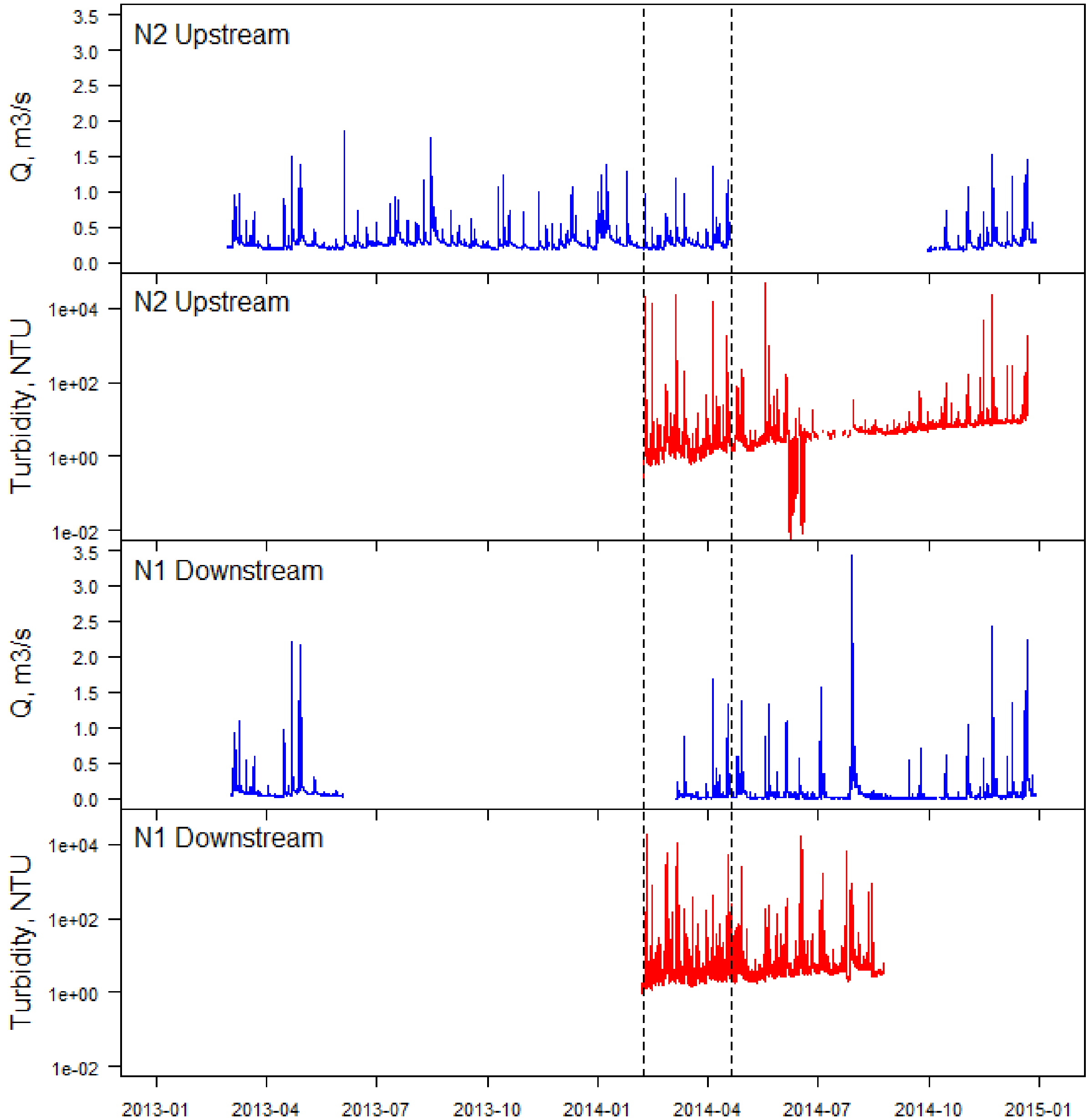

Figure A14. Streamflow (Q) and turbidity at N2 (upstream) and N1 (downstream) during the entire project period. Time labels are in Year-Month. Vertical dashed lines indicate the period of high quality measurements for detailed analysis of up-downstream differences in turbidity.

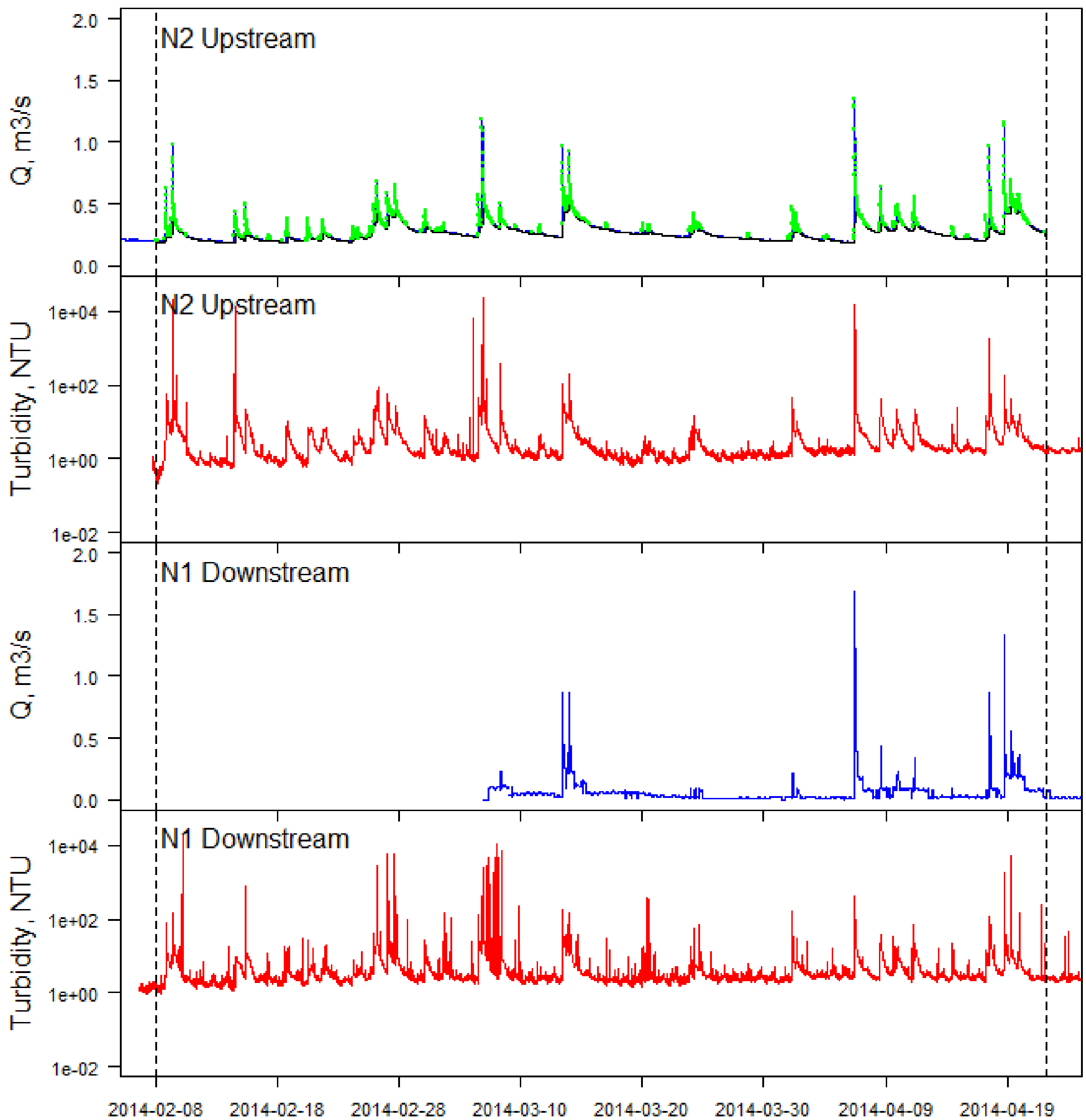

Figure A15. Streamflow (Q) and turbidity at N2 (upstream) and N1 (downstream) during the period with high quality measurements. Green dots on Q for N2 indicate where Q was defined as stormflow using baseflow separation and a stormflow threshold of 0.01 m3/s. Time labels are in Year-Month-Day. Dashed lines correspond to the dashed lines in Figure A14.

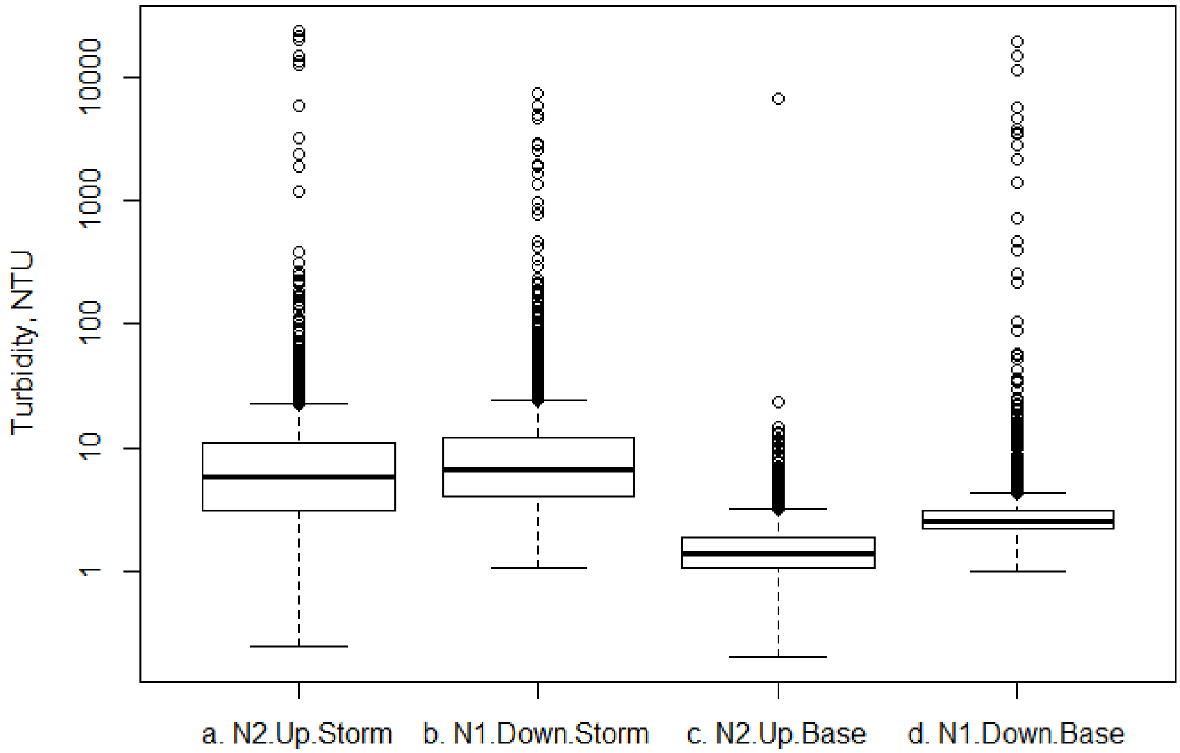

Figure A16. Boxplot of turbidity for stormflow and baseflow at N2 (upstream) and N1 (downstream), showing that turbidity was similar at the two sites during stormflow, and slightly higher downstream (N1) compared with upstream (N2) for baseflow conditions.

Nutrient concentrations

Nutrient concentrations were analyzed for 6 different storms at Nu'uli. Volume-weighted mean (VWM) concentrations of NO3 were similar at the forest (N2) and village (N1) sites for most storms (Figure A17). VWM PO4 was higher at the forest site (N2) compared with the village site (N1) for 3 out of 5 storms. Though the VWM concentrations of NO3 were similar for the forest and village, some of the higher storm VWM concentrations were based on a single sample, which may not be representative of the storm VWM concentration. For high discharge, concentrations of NO3 at the village were higher than at the forest (Figure A18), which was similar to Faga'alu. Like at Faga'alu, some high NO3 concentrations were observed on the falling limb of the hydrograph (Figure A19, A20), indicating a subsurface source, though there were also high concentrations in baseflow prior to or at the beginning of the storm event, indicating high concentrations in groundwater or in-stream sources. More data is needed to assess nutrient concentrations at high flow in Nu'uli.

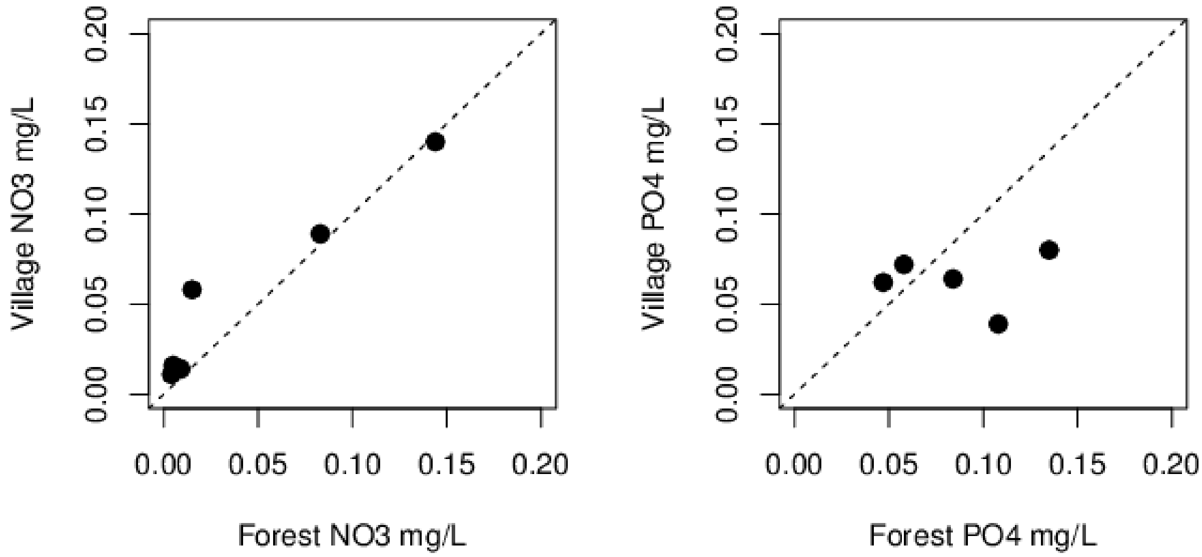

Figure A17. Volume-weighted mean concentration of nitrate and phosphate at the forest and village in Faga'alu during storm events. Dashed line is the 1:1 line.

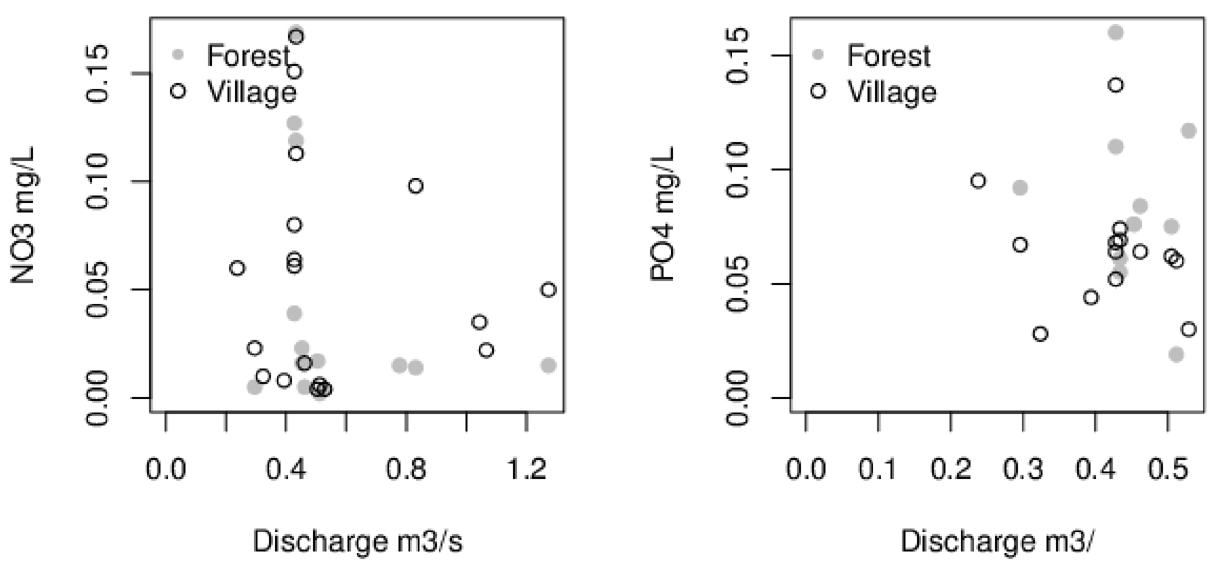

Figure A18. Concentration versus discharge for all storm samples at Nu'uli for nitrate (left) and phosphate (right).

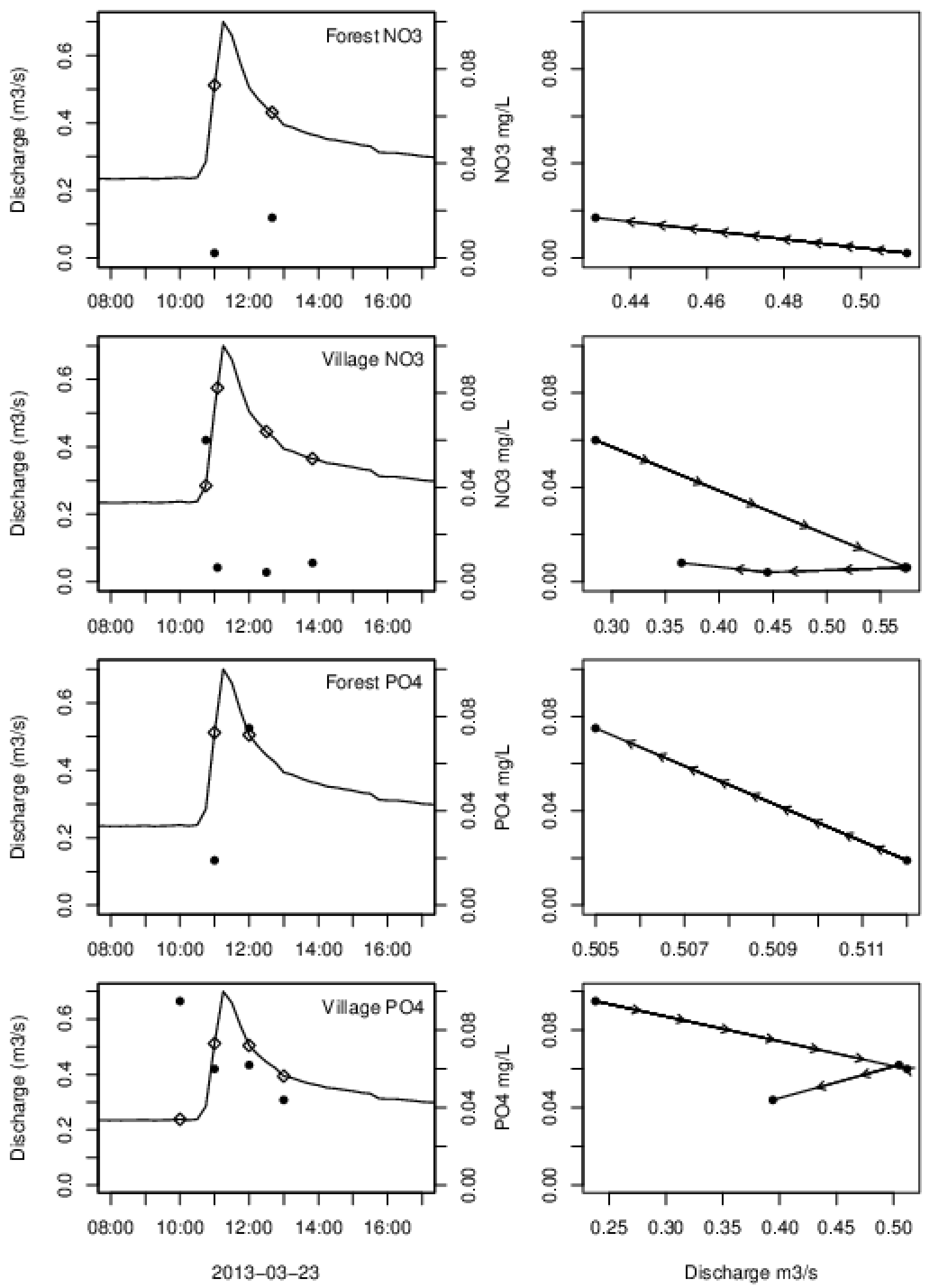

Figure A19. Time-series of discharge and concentration (left) and discharge-concentration relationships at Nu'uli for the storm on 2013-03-23 for nitrate and phosphate in the forest (N2) and village (N1) sites. Hollow diamonds in the left panels indicate the discharge at the sampled times, and black dots indicate concentrations.

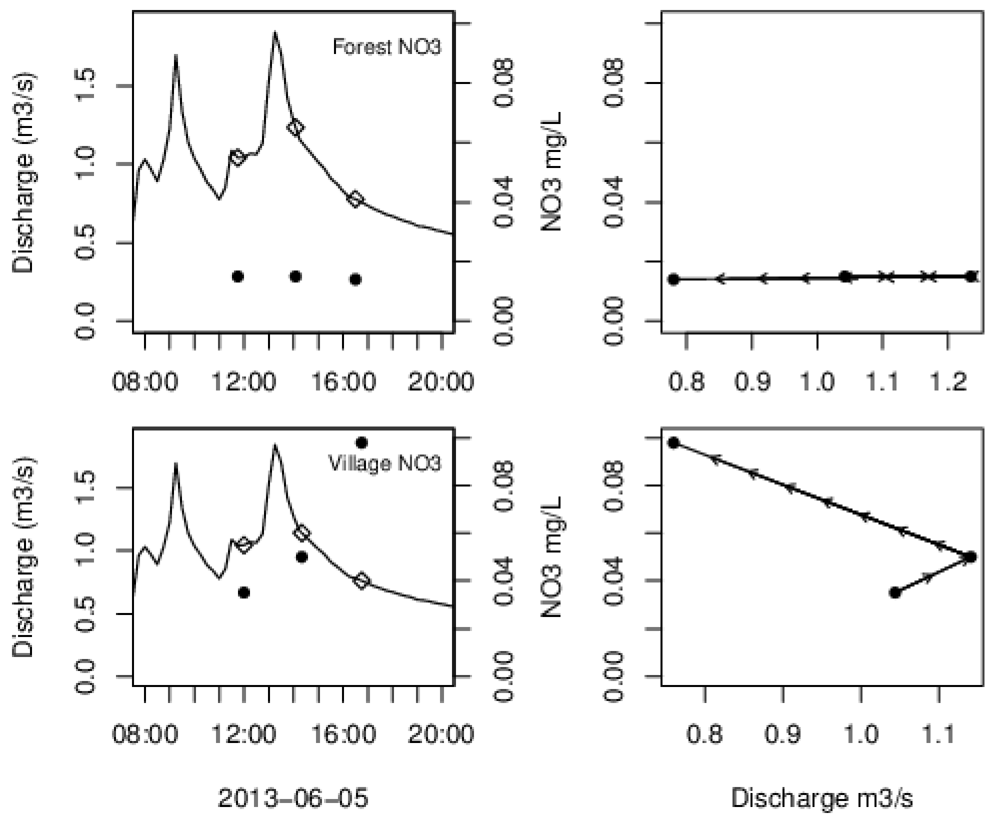

Figure A20. Time-series of discharge and concentration (left) and discharge-concentration relationships at Nu'uli for the storm on 2013-06-05 for nitrate and phosphate in the forest (N2) and village (N1) sites. Hollow diamonds in the left panels indicate the discharge at the sampled times, and black dots indicate concentrations.

Conclusion and future research directions

- Turbidity and suspended sediment concentrations were clearly impacted by humans at Faga'alu, while at Nu'uli turbidity was the same up and downstream of the village during stormflow, and was slightly higher at the downstream village site during baseflow. We conclude that there is no significant impact of human activity on turbidity at the stream sampled in Nu'uli, particularly during storm events.
- The modeling strategy for Faga'alu was revised to a much simpler statistical model that could be used in other watersheds, and was used to document the effectiveness of mitigation activities.
- Following mitigation activities at the quarry in Faga'alu, turbidity, SSC and suspended sediment yields downstream of the quarry were indistinguishable from the forest background, indicating that the mitigation was restorative of natural conditions. SSC and suspended sediment yield downstream of the village are still slightly elevated above the forest background.
- Stormwater had higher nitrate concentrations downstream of the village in Faga'alu, but not in Nu'uli, where concentrations downstream of the village were similar to that of the forest. Phosphate concentrations were similar to slightly lower downstream of the village compared with downstream of the forest in both Faga'alu and Nu'uli. We conclude that

nutrient concentrations at Nu'uli are similar to the forested background, but are higher at Faga'alu for nitrate.

- Phosphate concentrations were typically lower downstream of both village, though this could be due to sorption of phosphate onto suspended sediments in the stream rather than to lower concentrations of total phosphorus.
- The conclusions about nutrient concentrations are tentative, and depend on irregular sampling of hydrographs during storm events. A more thorough assessment of nutrient contamination could be performed using automated sampling at regular (e.g. 15 minute) intervals.