Watershed and oceanic controls on spatial and temporal patterns of sediment deposition in a fringing reef embayment: Faga’alu Bay, American Samoa

by

Messina, A.M.1\*, Biggs, T.W.1, Storlazzi, C.D.2

1 San Diego State University, Department of Geography, San Diego, CA 92182, amessina@rohan.sdsu.edu, +1-619-594-5437, tbiggs@mail.sdsu.edu, +1-619-594-0902

2 US Geological Survey, Pacific Coastal and Marine Science Center, Santa Cruz, CA 95060, cstorlazzi@usgs.gov, +1-831-460-7521, ocheriton@usgs.gov, +1-831-460-7579

Abstract

Keywords:

coral reefs,

Introduction

Problem

Increased suspended sediment concentrations over corals can reduce the health of coral reefs by attenuating light used for photosynthesis (Storlazzi et al. 2015), interfering with coral spawning, and reducing herbivory of turf algae (Bellwood and Fulton 2008; Goatley and Bellwood 2012). Increased sediment accumulation rates can reduce the health of coral reefs by blocking all light for photosynthesis, blocking sites for larval recruitment, requiring energy expenditure from the coral to self-clean, and triggering a breakdown of coral tissue as sediment kills coral polyps (Weber et al. 2012). In general, finer terrigenous sediment with more organic material is more detrimental to coral health by more effectively attenuating PAR, and the weird tissue breakdown thing. Finer sediment is most easily resuspended and potentially advected from the reef, or persist in suspension. The impact of both suspended and accumulated sediment is determined by the duration and intensity of the exposure, which are controlled by the input and residence time of sediment (exposure=duration x intensity) and the hydrodynamic conditions over the reef.

Interaction of loading and hydrodynamics

The complex spatial and temporal interaction of terrigenous sediment inputs and hydrodynamic processes can significantly alter the quantity, composition, and residence time of sediment in coral reefs (Storlazzi et al. 2009). In contrast to many small, mountainous watersheds in temperate coastal regions where fluvial discharge and wave energy commonly coincide (Warrick et al. 2004), discharge, deposition, and reworking of flood sediment are often decoupled on tropical islands, causing high deposition rates and residence times of terrigenous sediment (Draut et al. 2009; Storlazzi et al. 2009). Conversely, seasonal wind and wave patterns in the Trade wind belt can be coupled with sediment discharge or resuspension to decrease sediment deposition and residence times (Hoitink and Hoekstra 2003; Muzuka et al. 2010). Given the increased SSY to coastal waters caused by anthropogenic watershed disturbance on many tropical islands in the South Pacific and elsewhere (Messina and Biggs; Hettler et al. 1997; Ramos-Scharrón and Macdonald 2007; Bégin et al. 2014), an integrated understanding of how flood-supplied terrigenous sediment and water circulation control sediment deposition and residence time is essential for identifying and mitigating coral health impacts (Draut et al. 2009).

Due to logistical constraints, many conservation planning and remediation studies often use coarse estimates of pollutant discharge and distance-based plume models that assume symmetry in flow fields (Klein et al. 2012). Some studies correlate long term sediment accumulation, and by extension decreased coral health, with increased suspended sediment yield (SSY) from the watershed (Ryan et al. 2008), but there is also evidence of hydrodynamics decreasing sediment residence time in two ways: 1) by flushing suspended sediment away from the corals before it can be deposited (residence time = 0 min), and 2) resuspending and removing sediment that has been previously deposited (Hoitink and Hoekstra 2003).

Measurement Methods

Many researchers and environmental managers are interested in determining the location and severity of terrigenous sediment impacts on coral health, but developing a measure of sediment impact has proven difficult. Tube traps are the most common method for measuring sediment accumulation in shallow coral reef environments (White 1990; Storlazzi et al. 2011), but it is difficult to determine if these are ecologically meaningful indicators of coral stress. Some corals are well-adapted to turbid conditions (Perry et al. 2012), and deposited sediment can be removed actively by the coral itself, or passively by wave action before it is lethal. The stress on the coral organism increases linearly with the deposition amount and the duration of exposure (Fabricius 2005) but tube traps overestimate deposition and do not allow for sediment resuspension, making it impossible to evaluate the residence time of deposited sediment (Storlazzi et al. 2011). To more accurately quantify “net” sediment accumulation, Field et al. (2012) proposed the use of “SedPods” where a flat surface allows for resuspension, similar to the surrounding benthic substrate. While the complex interaction of sediment composition, hydrodynamics, and coral physiology are important, basic questions about location and controls on net terrigenous sediment accumulation rates are unknown at the study site.

Correlation with watershed loading

Several studies have found weak or no correlation between sediment trap collection and rainfall (Bothner et al. 2006; Victor et al. 2006) but it is well-known that SSY from small, mountainous watersheds can be poorly correlated with precipitation (Basher et al. 2011; Duvert et al. 2012). By correlating sediment trap accumulation with measured and modeled SSY from the watershed, this research proposes to develop a model of spatially distributed, monthly sediment accumulation as a function of watershed inputs and hydrodynamic conditions. The proposed modeling approach is similar to other efforts that have attempted to limit the complexity of the modeling approach, but still account for the impact of ocean conditions on sediment dynamics (Fabricius et al. 2012)

Research Questions

The research questions for this paper are:

What controls the spatial distribution of sediment accumulation, and can it be predicted by the flow velocities of water over the reef and distance from the stream mouth?

How do flood-supplied terrigenous sediment and hydrodynamic conditions interact to control the gross and net rate of terrigenous sediment deposition at monthly time scales in a coral reef embayment?

Materials and Methods

*Study area*

Faga'alu Bay is a v-shaped embayment situated on the western side of Pago Pago Bay, on the island of Tutuila, American Samoa (14.290˚ S, 170.677˚ W; Figure 1). The bay is surrounded by high topography that blocks wet-season northerly winds from October to April, but is exposed to dry-season southeasterly trade winds and accompanying short-period wind waves from May to September (Craig 2009). A semi-diurnal, microtidal regime exposes parts of the shallow reef crest and reef flat at extreme low tides. Faga'alu Bay is only open to south to southeast swell directions, and the more southerly angled swell must refract to the west, resulting in a reduction of wave energy. Offshore significant wave heights (*Hs*) are generally less than 2.5 m and rarely exceed 3.0 m. Peak wave periods (*Tp*) are generally about 9 s or less, rarely exceed 13 s, but occasionally reach 25 s during austral winter storms (Thompson and Demirbilek 2002). O. Vetter (unpublished data) recorded *Hs* up to 1.7 m on the fore reef in Faga'alu, but *Hs* greater than 1.0 m were rare. Tropical cyclones typically occur in the South Pacific from November to April (Militello et al. 2003), impacting American Samoa every 1-13 years since 1981 (Craig 2009), though high waves impacting the reefs without the storm making landfall occurs more frequently (Feagaimaalii-Luamanu 2016).

Faga’alu Bay is adjacent to a small (2.48 km2), steep-sided watershed that discharges terrigenous sediment during storm events from a perennial stream in the northwest corner of the Bay, and several surrounding ephemeral streams (Messina and Biggs, In Press). The bathymetrically complex reef is characterized by a shallow reef flat extending from shore to the reef crest, where it descends at an approximately 1:1 slope to an insular shelf at approximately 20 m depth. Near the reef crest, the reef flat is primarily cemented reef pavement, but within a few 10s of m, transitions into thickets of primarily *Acropora spp.* An anthropogenically-altered, vertical-walled, 5-15 m deep paleostream channel (Figure 1) extends from the outlet of Faga'alu Stream eastward to Pago Pago Bay; this channel divides the reef into a larger, more exposed southern section (“southern reef” in Figure 1), and a smaller, more sheltered northern section (“northern reef” in Figure 1). Closer to the shore in the southern back-reef there are areas of deeper (1-5 m) sediment-floored pools with coral bommies (“back-reef pools” in Figure 1). See Cochran et al. (2016) for a detailed description of the bathymetry. Surveys in 2015 found coral coverage varied from less than 10% on the degraded northern reef, to more than 50% on the more intact southern reef (Cochran et al. 2016).

Measuring sediment accumulation on the reef

Deploying a TUBE in conjunction with a SedPod will allow comparison of gross and net sediment accumulation, and an assessment of the interaction of sediment loading and removal at time scales relevant to coral mortality and management. SedPods and TUBEs, deployed at nine locations on the reef flat (water depth 1-2 m) and reef crest (10-15 m) in Faga’alu Bay (**Error! Reference source not found.**), are being collected monthly to provide data on sediment accumulation rates (mg/cm2/d) and composition from February 2014 through January 2015. Collection will be performed by Messina when in the field and by the Department of Marine and Wildlife Resources (DMWR) staff when Messina is not on-island. Sediment samples collected in tubes and SedPods will be wet sieved to the rinse salt from the sample and assess particle size (sand or fines). The samples will be dried and weighed to determine bulk sediment weight before being shipped to SDSU to characterize the geochemical composition (percent terrigenous, carbonate and organic) using Loss on Ignition (LOI) method (Heiri et al. 2001; Santisteban et al. 2004).

Monthly sediment accumulation may be a function of sediment loading and hydrodynamic processes interacting on daily time scales, where hydrodynamic conditions only on the day of sediment discharge and not the mean monthly condition, are important. If monthly sediment loading and monthly mean residence time do not adequately predict sediment accumulation in the sediment traps, it might be necessary to investigate sediment loading and water residence times on daily scales, and further refine the statistical analysis and equations. In that case, daily sediment loading and daily mean residence time will be used to assess daily deposition, which can be compared to the monthly sediment accumulation measurements.

Modeling sediment accumulation

Univariate and multi-variate linear regression models were used to establish the relative controls of suspended sediment yield from the watershed (SSY, tons) and mean monthly wave height (MMWH, m) on sediment accumulation rates, both the average for North and South reefs, and at each of the nine locations where accumulation is measured. Sediment loading from the watershed in month *t* (Sw(t)) will be calculated using the model from Paper One:

|  |  |  |
| --- | --- | --- |
|  |  | Equation 7 |
| where SW is the sum of *SSYi* for n events in the month, calculated from Equation 4. | | |

Temporal distribution of sediment accumulation

Two time scales of analysis will be used: monthly and seasonal (dry and wet season). A monthly time interval was chosen to correspond with other studies found in the literature (Victor et al. 2006; Muzuka et al. 2010), to include enough storm events to collect enough sediment for analysis, and for logistical reasons due to the high spatial coverage of sites and limited field personnel and resources. Assessing differences between dry and wet season sediment dynamics is useful to determine if there are seasonal patterns or modes that may be relevant to long term sediment accumulation (Ryan et al. 2008) or coral conservation and restoration (Muzuka et al. 2010). It is hypothesized that net deposition predominantly characterizes the wet season, and a net sediment removal, or limited deposition, predominantly characterizes in the dry season (**Error! Reference source not found.**).

Spatial distribution of sediment accumulation

An important consideration for coral conservation is determining the spatial distribution of sediment impacts. To explain the relative spatial variation of sediment accumulation among sediment traps, and to determine if flow direction or distance from the stream is more important, all sediment accumulation measurements will be normalized by the maximum of the measured accumulation at the nine traps for a given month. Normalized values are then modeled as a function of flow velocity (towards/away the stream mouth) and distance from the stream mouth:

|  |  |  |
| --- | --- | --- |
|  |  | Equation 9 |
| where is the monthly sediment accumulation measured at trap *i in month t* SedAccMax is the highest observed sediment accumulation of all sediment traps in month t, *Vϴi* is mean flow velocity in the direction away from the stream mouth at location *i* in month *t,* and *di* is distance from the stream mouth at location *i.* | | |

## Expected Results/Outcomes

The proposed work will characterize and quantify the amount, composition, and particle sizes of sediment contributing to coral reef degradation in Faga’alu, informing mitigation strategies to reduce terrestrial sediment loading to the priority coral reef. The work will establish a baseline to measure the performance of future mitigation projects by developing a model that relates sediment loading from the watershed to sediment accumulation on the reef under varying oceanographic conditions.

Pomeroy 2015 good paper

Results

Discussion

Acknowledgements

This work was carried out in collaboration between San Diego State University and the US Geological Survey's Pacific Coral Reef Project. Funding was provided by the NOAA Coral Reef Conservation Program and the US Geological Survey's Coastal and Marine Geology Program. We would like to thank Dr. Michael Favazza for providing logistical support in the field. We would also like to thank Liv Herdman (USGS) and three anonymous reviewers who contributed excellent suggestions and timely reviews of our work. Use of trademark names does not imply USGS endorsement of products.

References

Basher L, Hicks D, Clapp B, Hewitt T (2011) Sediment yield response to large storm events and forest harvesting, Motueka River, New Zealand. New Zeal. J. Mar. Freshw. Res. 45:333–356

Bégin C, Brooks G, Larson R a., Dragićević S, Ramos Scharrón CE, Coté IM (2014) Increased sediment loads over coral reefs in Saint Lucia in relation to land use change in contributing watersheds. Ocean Coast. Manag. 95:35–45

Bellwood DR, Fulton CJ (2008) Sediment-mediated suppression of herbivory on coral reefs: Decreasing resilience to rising sea-levels and climate change? Limnol. Oceanogr. 53:2695–2701

Bothner MH, Reynolds RL, Casso MA, Storlazzi CD, Field ME (2006) Quantity, composition, and source of sediment collected in sediment traps along the fringing coral reef off Molokai, Hawaii. Mar. Pollut. Bull. 52:1034–47

Cochran SA, Gibbs AE, D’Antonio NL, Storlazzi CD (2016) Benthic habitat map of U.S. Coral Reef Task Force Faga‘alu Bay priority study area, Tutuila, American Samoa: U.S. Geological Survey Open-File Rport 2016-XXXX, XX.

Craig P (2009) Natural History Guide to American Samoa. National Park of American Samoa, Pago Pago, American Samoa

Draut AE, Bothner MH, Field ME, Reynolds RL, Cochran, S.A.Logan JB, Storlazzi CD, Berg CJ (2009) Supply and dispersal of flood sediment from a steep, tropical watershed: Hanalei Bay, Kaua’i, Hawai'i, USA. Geol. Soc. Am. Bull. 121:574–585

Duvert C, Nord G, Gratiot N, Navratil O, Nadal-Romero E, Mathys N, Némery J, Regüés D, García-Ruiz JM, Gallart F, Esteves M (2012) Towards prediction of suspended sediment yield from peak discharge in small erodible mountainous catchments (0.45–22km2) of France, Mexico and Spain. J. Hydrol. 454-455:42–55

Fabricius KE (2005) Effects of terrestrial runoff on the ecology of corals and coral reefs: review and synthesis. Mar. Pollut. Bull. 50:125–46

Fabricius KE, De’ath G, Humphrey C, Zagorskis I, Schaffelke B (2012) Intra-annual variation in turbidity in response to terrestrial runoff on near-shore coral reefs of the Great Barrier Reef. Estuar. Coast. Shelf Sci. 1–9

Feagaimaalii-Luamanu J (2016) High surf generated by TC Victor washes over roads and property. Samoa News

Field ME, Chezar H, Storlazzi CD (2012) SedPods: a low-cost coral proxy for measuring net sedimentation. Coral Reefs

Goatley CHR, Bellwood DR (2012) Sediment suppresses herbivory across a coral reef depth gradient. Biol. Lett. 8:1016–8

Heiri O, Lotter AF, Lemcke G (2001) Loss on ignition as a method for estimating organic and carbonate content in sediments : reproducibility and comparability of results. J. Paleolimnol. 25:101–110

Hettler J, Irion G, Lehmann B (1997) Environmental impact of mining waste disposal on a tropical lowland river system: a case study on the Ok Tedi Mine, Papua New Guinea. Miner. Depos. 32:280–291

Hoitink AJF, Hoekstra P (2003) Hydrodynamic control of the supply of reworked terrigenous sediment to coral reefs in the Bay of Banten (NW Java, Indonesia). Estuar. Coast. Shelf Sci. 58:743–755

Klein CJ, Jupiter SD, Selig ER, Watts ME, Halpern BS, Kamal M, Roelfsema C, Possingham HP (2012) Forest conservation delivers highly variable coral reef conservation outcomes. Ecol. Appl. 22:1246–56

Messina AT, Biggs TW Contributions of human activities to suspended sediment yield during storm events from a steep, small, tropical watershed: Faga’alu, American Samoa. J. Hydrol.

Militello A, Scheffner NW, Thompson EF (2003) Hurrican-Induced Stage-Frequency Relationships for the Territory of American Samoa. USACOE Technical Report CHL-98-33.

Muzuka ANN, Dubi AM, Muhando CA, Shaghude YW (2010) Impact of hydrographic parameters and seasonal variation in sediment fluxes on coral status at Chumbe and Bawe reefs, Zanzibar, Tanzania. Estuar. Coast. Shelf Sci. 89:137–144

Perry C, Smithers SG, Gulliver P, Browne NK (2012) Evidence of very rapid reef accretion and reef growth under high turbidity and terrigenous sedimentation. Geology 40:719–722

Ramos-Scharrón CE, Macdonald LH (2007) Measurement and prediction of natural and anthropogenic sediment sources, St. John, US Virgin Islands. Catena 71:250–266

Ryan KE, Walsh JP, Corbett DR, Winter a (2008) A record of recent change in terrestrial sedimentation in a coral-reef environment, La Parguera, Puerto Rico: a response to coastal development? Mar. Pollut. Bull. 56:1177–83

Santisteban JI, Mediavilla R, Lopez-Pamo E, Dabrio CJ, Zapata MBR, Garcia MJG, Castano S, Martínez-Alfaro PE (2004) Loss on ignition: a qualitative or quantitative method for organic matter and carbonate mineral content in sediments? J. Paleolimnol. 32:287–299

Storlazzi CD, Field ME, Bothner MH (2011) The use (and misuse) of sediment traps in coral reef environments: theory, observations, and suggested protocols. Coral Reefs 30:23–38

Storlazzi CD, Field ME, Bothner MH, Presto MK, Draut AE (2009) Sedimentation processes in a coral reef embayment: Hanalei Bay, Kauai. Mar. Geol. 264:140–151

Storlazzi CD, Norris BK, Rosenberger KJ (2015) The influence of grain size, grain color, and suspended-sediment concentration on light attenuation: Why fine-grained terrestrial sediment is bad for coral reef ecosystems. Coral Reefs 34:967–975

Thompson EF, Demirbilek Z (2002) Wave Response, Pago Pago Harbor, Island of Tutuila, Territory of American Samoa. USACOE Coastal and Hydraulics Laboratory ERDC/CHL TR-02-20.

Vetter O (2013) Inter-Disciplinary Study of Flow Dynamics and Sedimentation Effects on Coral Colonies in Faga’alu Bay, American Samoa: Oceanographic Investigation Summary. NOAA CRCP Project #417.

Victor S, Neth L, Golbuu Y, Wolanski E, Richmond RH (2006) Sedimentation in mangroves and coral reefs in a wet tropical island, Pohnpei, Micronesia. Estuar. Coast. Shelf Sci. 66:409–416

Warrick JA, Mertes LAK, Washburn L, Siegel DA (2004) Dispersal forcing of southern California river plumes, based on field and remote sensing observations. Geo-Marine Lett. 24:46–52

Weber M, de Beer D, Lott C, Polerecky L, Kohls K, Abed RMM, Ferdelman TG, Fabricius KE (2012) Mechanisms of damage to corals exposed to sedimentation. Proc. Natl. Acad. Sci. 109:E1558–E1567

White J (1990) The use of sediment traps in high-energy environments. Mar. Geophys. Res. 12:145–152

Tables

Figure Captions

Figure xxx. Hypothetical phasing of monthly sediment loading from the watershed and offshore wave height *(Draut et al. 2009)*. Red shaded areas indicate a time of net terrigenous sediment accumulation and green shaded areas indicate a time of net terrigenous sediment removal and resuspension of marine-derived sediment.