This PDF file is a digital version of a chapter in the 2005 GWS Conference Proceedings. Please cite as follows:

Harmon, David, ed. 2006. *People, Places, and Parks: Proceedings of the 2005 George Wright Society Conference on Parks, Protected Areas, and Cultural Sites.* Hancock, Michigan: The George Wright Society.

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Spatial and Temporal Patterns in Sediment Collection Rates on Coral Reefs at War in the Pacific National Historical Park, Territory of Guam

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Introduction

On Guam, sedimentation resulting from poor land management is the single greatest anthropogenic impact on coastal reefs (Birkeland et al. 2000). Over the last 25 years, increases in population and changes in land practices have led to significant increases in terrestrial runoff (National Resource Conservation Service 1996), and associated declines in coral abundance, cover, and recruitment (Richmond 1994, 1995; Wolanski et al. 2003a).

Sediments can bury adult and juvenile corals (Richmond 1994; Rogers 1990), impair reproduction (Richmond 1993, 1995), and locally reduce recruitment rates (Hodgson 1990; Gilmour 1999) and juvenile survival (Richmond 1995). While sediment impacts may not always be lethal, coral reef decline may be subtly linked to sediment runoff from adjacent watersheds when sub-lethal affects impair the coral's ability to recover from acute shock, such as tropical cyclones or crown-of-thorn starfish outbreaks (Wolanski et al. 2003b).

War in the Pacific National Historical Park manages 180 ha of coral reef in the Asan Watershed. The coastal edge of the watershed is well developed, containing a small village with a population of approximately 2,000 people (U.S. Census Bureau 2001). Inland, the watershed is protected by its inclusion within the national park, but is still impacted by frequent wildland fires, off-road vehicles, and development along its boundary, all of which contribute to increased soil erosion (National Park Service, unpublished data). Sediment plumes within War in the Pacific are a frequent sight following even modest rains.

Site-specific information on sedimentation rates is needed by park resource managers to assess the magnitude and characteristics of this potentially serious impact to War in the Pacific's principal marine natural resource. This project examined spatial and temporal patterns of sediment collection rates on the park reefs to gather this critical information needed to better target the park's coral reef management activities.

Methods

Sediment collectors, consisting of three polyvinyl chloride (PVC) tubes 5 cm in diameter by 13 cm long, were installed 50 cm off the bottom at 25 sites along the fore reef of the Asan Beach Unit of War in the Pacific (Figure 1). Trap dimensions were based on recommendations of Gardner (1980) and English et al. (1997) to avoid over- and under-sampling. At each study site, two collectors were installed, one each at depths of 10 and 20 m. Sites were spaced approximately 150 m apart. After three weeks, collectors were capped, collected by scuba divers and returned to the laboratory for further processing. New collectors were installed simultaneously. Seventeen temporal replicates were run between 15 September 2003 and 18 November 2004.

Sediments from two of the three tubes were filtered, dried for 24 hours at 100°C in a muffle furnace (Thermolyne F62700), and weighed. Approximately 1 g of sediment was sub-sampled and burned in porcelain crucibles at 550°C and 1000°C for 1 hour each to determine the percentage of organic and non-$CaCO_3$ material in the samples. Non-$CaCO_3$ material in marine sediments can be used as a measure of terrestrial inputs on coral reefs where marine sediments are almost exclusively composed of $CaCO_3$. Upland soils in the Asan Watershed are primarily basaltic in origin, but with some limestone (Young 1988), so the percentage of non-$CaCO_3$ material in our samples underestimates the contribution of terrestrial material to the sediments on park reefs. Sediments from the third tube were processed as part of another project and will not be discussed here.

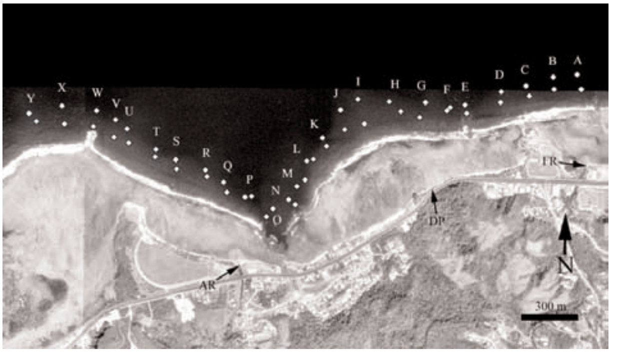

Figure 1. Sediment study sites along the fore reef of Asan Bay. AR = Asan River, DP = Drainage Pipe, FR = Fonte River.

Daily sediment collection rates in $g/cm^2/day$ were calculated by dividing gross sediment weights by the surface area of the tube opening and the total number of days left *in situ*. Daily rainfall data were obtained from the National Weather Service at Tiyan, Guam. Distances from the nearest point source were measured for each sediment collector in ArcGIS using a straight line extending from the center of the river mouth or drainage pipe to the location of each sediment collector.

Data were analyzed using a reduced general linear model with terms for time (replicate), location, and depth. Missing samples in some replicates precluded a full model analysis, and the interaction terms could not be included and were assumed to be non-significant. Pearson correlation coefficients were used to examine spatial relationships within the data. The Minitab statistical package was used for all analyses.

Results

Sediment collection rates (Figure 2) showed a significant spatial pattern (ANOVA; $F=10.78$; $df=24,606$; $p<0.001$). Sediments downstream of the Asan River (sites L–O) and near Adelup Point (sites A–D) all have elevated sediment collection rates. The 20-m collec-

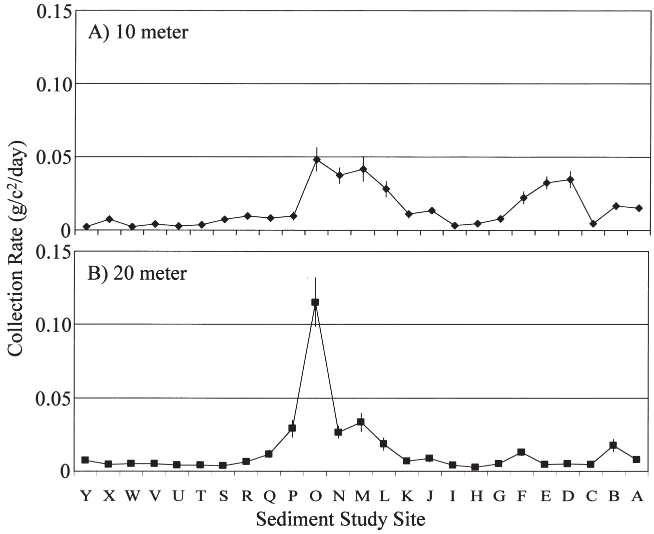

Figure 2. Mean (error bars = ±1 standard error) sediment collection rates ($g/cm^2/day$) at (a) 10-m-deep and (b) 20-m-deep sediment study sites in Asan Bay. Site reference letters correspond with site locations in Figure 1.

tors at site O had the highest average collection rate, 2.302 ± 2.389 $g/cm^2/day$. The lowest sediment collections rates were observed upstream of Asan River (sites S–Y). The 20-m collectors at Site W had the lowest average collection rate, 0.045 ± 0.031 $g/cm^2/day$. No significant difference in collection rate was found between the 10- and 20-m traps (ANOVA; F=2.32; df=1,606; p=0.128).

Sites with high sediment loads were adjacent to sediment point sources. The Asan River drains just west of the Asan Cut, an intermittent storm drainage pipe empties into park waters inshore of site F, and the Fonte River enters just east of Adelup Point, inshore from site A (Figure 1). Sediment collection rates declined significantly with distance downstream from a sediment point source (Pearson Correlation; r=–0.304, p<0.001)

Sediment collection rates varied significantly with time (ANOVA; F=16.38; df=16,606; p<0.001). Guam has pronounced wet (July–December) and dry (January–June) seasons, and the average daily rainfall for the replicates collected during the 2004 dry season (0.400 ± 0.043 cm/day) was approximately one-third of that for replicates collected during the 2003 (1.145 ± 0.115 cm/day) and 2004 (1.520 ± 0.405 cm/day) wet seasons. Sediment collection rates during the 2004 dry season (Figure 3) were approximately half of those observed during the 2003 and 2004 wet season: 0.175 ± 0.036 $g/cm^2/day$ compared with 0.364 ± 0.051 and 0.380 ± 0.037 $g/cm^2/day$, respectively (ANOVA; F=8.92; df=2,620; p<0.001).

Mean percent non-$CaCO_3$ material in the sediment samples varied from 53.4% to 65.9%, but showed no spatial relationship to sediment point sources (Pearson Correlation; r=–0.053; p=0.716).

Discussion

Sedimentation rates on Guam are believed to have increased over the last 25 years as a result of population growth and poor land management practices (National Resource Con-

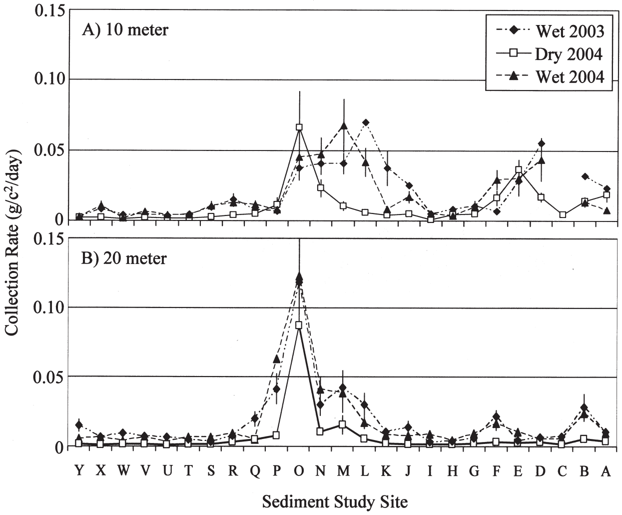

Figure 3. Mean (error bars = ±1 standard error) sediment collection rates (g/cm^2/day) by season at (a) 10-m-deep and (b) 20-m-deep sediment study sites in Asan Bay. Site reference letters correspond with site locations in Figure 1.

servation Service 1996). In the Asan watershed, inadequate enforcement of environmental regulations, poor erosion control associated with development, and wildland arson all contribute to increased soil erosion and subsequent sedimentation on the park's coral reefs.

The sediment collection rates measured in this study are among the highest reported in the literature. Numerous studies conducted on the Great Barrier Reef using comparable methods (Mapstone et al. 1989; Hopley et al. 1990) found sediment collection rates 1–3 orders of magnitude lower than the peak rates observed at War in the Pacific. Rates reported from the Caribbean tend to be even lower than those reported for the Great Barrier Reef (Hopley et al. 1990; Rogers 1990).

Sediment collection rates were correlated with distance downstream from the nearest point source. Point source, as opposed to non-point source runoff, appears to be the primary avenue for sediment transport from the Asan watershed onto the adjacent reef. While no significant difference in sediment collection rate was found between 10- and 20-m collectors, plume effects were more evident in shallow water, suggesting influxing sediments were moving parallel to the reef crest and not being transported offshore. After some rain events, we observed sediment plumes 2–3 m thick floating on the ocean surface and moving parallel to the reef crest. Similar plumes have been documented at Fouha Bay on southern Guam (Wolanski et al. 2003a).

On Guam, the peak coral spawning and larval settlement occurs during the wet season (Richmond and Hunter 1990), when sediments are at their highest. Early life history stages and processes (e.g., larval survival and settlement) may be adversely affected by even low sediment concentrations (Hodgson 1990, Gilmour 1999).

After reviewing numerous sedimentation studies, Rogers (1990) concluded that sediment collection rates over 0.01 g/cm^2/day were sufficient to cause negative impacts on corals. Pastorak and Bilyard (1985) predicted, based on sedimentation data collected in Guam by

Randall and Birkeland (1978), severe to catastrophic impacts on coral reefs at chronic sedimentation rates >0.05 $g/cm^2/day$. However, healthy coral reefs have been observed in nearshore areas where sediment inputs are common, suggesting that these reefs may be adapted to intense sediment regimes (Ayling and Ayling 1998). Coral communities may also be able to adapt to chronic, elevated sediment conditions, allowing them survive in areas receiving consistent but elevated sediment inputs (e.g., river mouths). Most studies have examined sediment stress on adult corals, but other life history stages can be adversely affected by significantly lower sediment inputs than adult corals (Hodgson 1990; Gilmour 1999). Considerable discussion regarding the validity (and value) of these thresholds has been going on for many years, and with the present data, establishing a single threshold limit is probably impossible. Regardless, sediment collection rates observed in this study are orders of magnitude greater than all published thresholds, raising concern for the future health of the park's coral reefs.

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