Environ Monit Assess (2009) 150:157–165
DOI 10.1007/s10661-008-0674-y

Assessing coastal waters of American Samoa: territory-wide water quality data provide a critical "big-picture" view for this tropical archipelago

Guy T. DiDonato · Eva M. DiDonato · Lisa M. Smith · Linda C. Harwell · J. Kevin Summers

Received: 28 February 2008 / Accepted: 29 February 2008 / Published online: 11 December 2008

Abstract The coastal waters of American Samoa's five high islands (Tutuila, Aunu'u, Ofu, Olosega, and Ta'u) were surveyed in 2004 using a probabilistic design. Water quality data were collected from the near-shore coastal habitat, defined as all near-shore coastal waters including embayments, extending out to 1/4 mile off-shore. Hydrography and water column samples were collected, and water quality data were compared to the Territorial water quality standards for pH, dissolved oxygen (DO), *Enterococcus*, chlorophyll a, water clarity, total nitrogen, and total phosphorus. All station measurements for pH, DO, and *Enterococcus* satisfied the local water quality standards, although some fraction of the Territory could not be assessed for either DO or *Enterococcus*. With respect to chlorophyll a, $66 \pm 18\%$ of Territory coastal waters complied with the standard, while $34 \pm 18\%$ failed to comply with the standard. For water clarity, $54 \pm 18\%$ of the Territorial waters complied with the standard while $42 \pm 7\%$ failed to comply. Territorial waters satisfied the standards for total nitrogen and phosphorus $72 \pm 17\%$ and $92 \pm 10\%$, respectively. These data provide the first "big-picture" view of water quality in the near shore region around the high islands of American Samoa. While the picture is encouraging, these data suggest emerging water quality concerns.

Keywords American Samoa · Coastal water quality · Probabilistic design · South Pacific

G. T. DiDonato (✉)
American Samoa Environmental Protection Agency,
Pago Pago, AS 96799, USA
e-mail: guy.didonato@noaa.gov

E. M. DiDonato
National Park of American Samoa,
Pago Pago, AS 96799, USA

L. M. Smith · L. C. Harwell · J. K. Summers
Gulf Ecology Division, US Environmental Protection
Agency, Gulf Breeze, FL 32561, USA

Present Address:
G. T. DiDonato
National Ocean Service, Hollings Marine Laboratory,
Charleston, SC 29412, USA

Present Address:
E. M. DiDonato
National Park Service Inventory and Monitoring
Program, Southeast Coast Network,
Sullivan's Island, SC 29482, USA

Introduction

American Samoa, located in the South Pacific approximately 4,500 km south-southwest of Hawaii, is the southernmost United States Territory. The Territory consists of five volcanic high islands (Tutuila, Aunu'u, Ofu, Olosega, and Ta'u) and two atolls (Rose and Swains) with a combined land area of nearly 200 km^2. The climate is tropical, with warm temperatures year-round. The year is divided into a dry season (June to November) dominated by the Trade winds and a wet season (November to May). Tutuila, the largest and westernmost of the high islands, receives up to 650 cm of rain annually.

Since 1980, human population in the Territory has increased from approximately 35,000 to over 60,000, more than 95% of which lives on Tutuila. This population growth rate (approximately 1.8% per year) is a major concern in American Samoa as increasing urbanization and other associated land use changes pose a threat to limited island natural resources (Craig et al. 2000). In particular, changes in watershed land use can negatively affect near-shore water quality (Smith et al. 2003). There is concern that water quality degradation will result in loss of marine resources (e.g., Fabricius 2005; Fabricius et al. 2005) and recreational opportunities (DiDonato and Paselio 2006), among other resource uses and benefits.

Despite concern over the potential impacts of increasing population and changing land use in American Samoa, there is very little information on the current status of coastal water quality. The work reported here, therefore, had two objectives. The first objective was to conduct a comprehensive survey of water quality indicators in the near-coastal waters of American Samoa. Our survey utilized the probabilistic design approach developed by the US Environmental Protection Agency (US EPA) to survey coastal resources (e.g., Macauley et al. 2002). In this design, sample locations are selected randomly within a defined spatial scale in order to produce an unbiased estimate of selected environmental parameters. In this case, the design targeted the coastal waters of the five main islands of the Territory to provide a Territory-wide estimate of water quality. The second objective of this study was to compare collected data with numerical criteria to develop a snapshot of current water quality condition. For this, we used the American Samoa Water Quality Standards (ASWQS) as our assessment criteria. The ASWQS were originally based on water quality standards used in Hawaii, but they were refined in the late 1970s using survey data from coastal waters, particularly those around Tutuila, in response to localized pollution within Pago Pago Harbor. The current version of these numerical criteria is used by the American Samoa Environmental Protection Agency (ASEPA) to assess the status of Territorial waters, as required under the Federal Clean Water Act, and are used to determine if coastal waters are in compliance ('pass') or out of compliance ('fail'). While monitoring data have demonstrated improvements in water quality within Pago Pago Harbor (e.g. Craig et al. 2005), there have been no studies to date examining water quality across the larger Territory. However, it is generally presumed that coastal water quality is good due to exchange with open ocean water.

Methods

Sampling design

This study utilized the US EPA's National Coastal Assessment protocol, which uses a probabilistic design, to assess the near-shore coastal waters of American Samoa. For this survey, the near-shore coastal habitat was defined as all near-shore coastal waters, including embayments, extending out to 1/4 mile off-shore, around the five high islands (Tutuila, Aunu'u, Ofu, Olosega and Ta'u). Fifty (50) stations were randomly selected using GIS (Figs. 1 and 2). Stations were visited once during 2004, with stations around Tutuila and Aunu'u sampled in April and May and those around Ofu, Olosega, and Ta'u, in August.

Field methods

Field methods were guided by the National Coastal Assessment Field Operations Manual (USEPA 2001). All water column samples and measurements were collected upon first arrival at each station. A hydrographic profile was collected using a datalogger (YSI 6000) suspended over the side of the boat. Dissolved oxygen (DO, mg/L), pH, temperature, and salinity were recorded at the surface, every meter down to 5 m, then every 5 m to near bottom or to the end of the field cable (25 m), whichever came first. For sites 1–2 m deep,

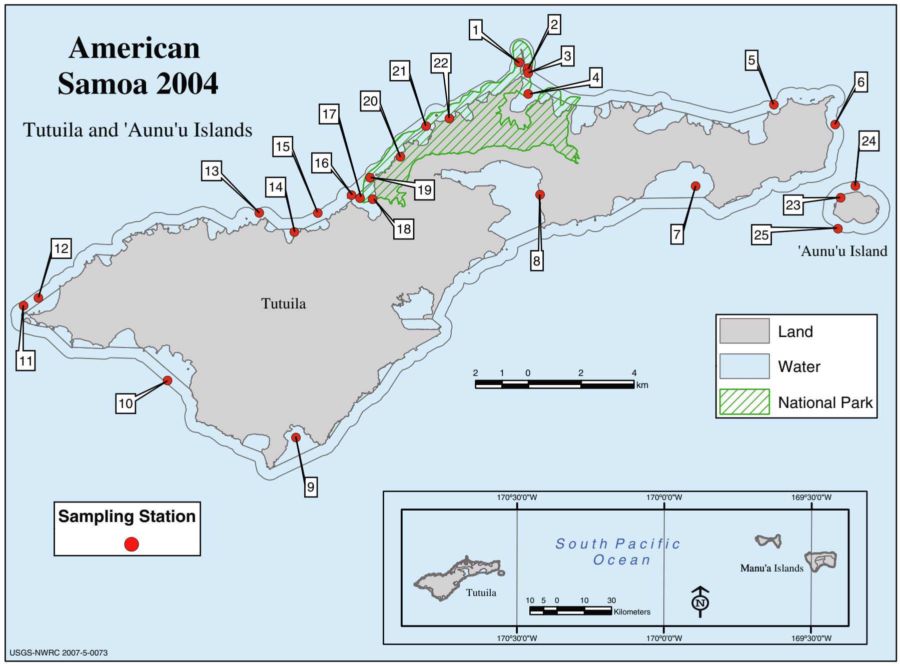

Fig. 1 Station locations around Tutuila and Aunu'u islands

a surface and bottom reading were taken; for sites <1 m deep, one reading was taken at mid-depth (USEPA 2001). Profile readings were recorded twice: once on the downcast and again on the upcast. Water column light penetration data were collected using a LiCor LI1000 by measuring near-simultaneous light readings using an ambient light sensor and an underwater (2 pi) cosine sensor. Light readings were done at the same depths as the hydrographic readings.

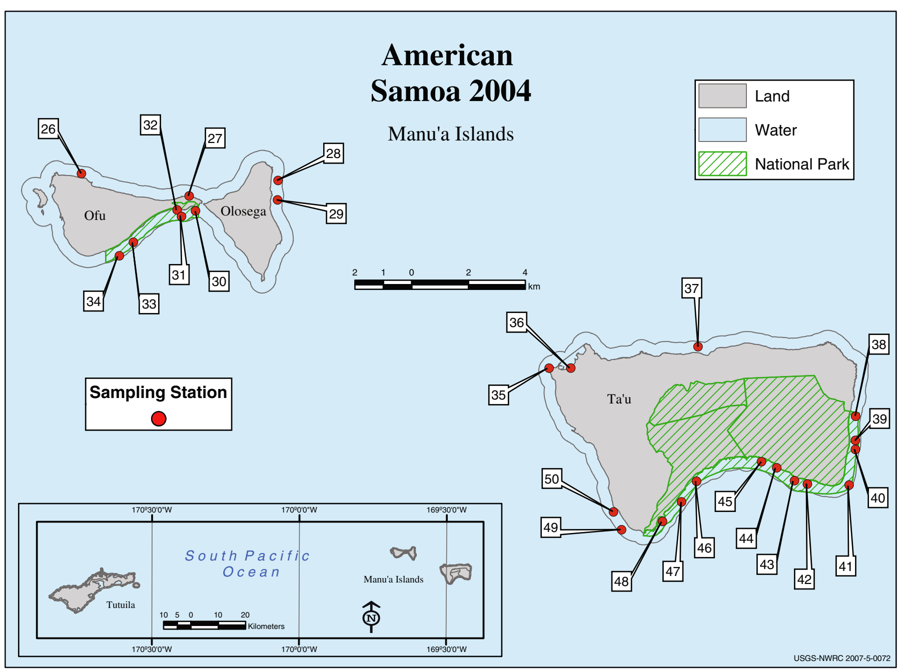

Fig. 2 Station locations around the Manu'a islands (Ofu, Olosega, and Ta'u)

Water samples for bacterial and nutrient analyses (including chlorophyll *a* and total suspended solids) were collected at each station using a Nisken bottle. Samples were taken at approximately 0.5 m below the surface, mid-water column, and approximately 0.5 m above bottom. For stations ≤ 1 m deep, a single sample was taken at mid-depth; for stations 1–2 m deep, a sample was taken approximately 0.5 m below surface and approximately the same distance above bottom. Bacterial samples were stored in sterile bottles, and water samples for nutrient analysis were stored in closed plastic containers. Both were held on ice until returned to the laboratory and processed. *Enterococcus*, the bacterial indicator used in American Samoa to assess impairment for body contact recreation (DiDonato and Paselio 2006), were enumerated within 24 h using Enterolert®. Because of the short holding time requirement, bacterial indicator sampling was only possible around Tutuila and Aunu'u. Water samples were processed to measure water column constituents. To quantify ammonium (NH_4), nitrite (NO_2), nitrate (NO_3), urea, phosphate (PO_4), and dissolved silicate (Si), water samples were filtered (GF/F). The material remaining on the filter paper was analyzed for chlorophyll *a* (Chl *a*) and total suspended solids (TSS). Unfiltered samples were analyzed for total nitrogen (TN) and total phosphorus (TP). All samples were frozen until laboratory analysis. For the purposes of this report, NH_4, NO_2, and NO_3 were summed to estimate dissolved inorganic nitrogen (DIN). Phosphate is dissolved inorganic phosphate and will hereafter be referred to as DIP.

Data analysis

Water quality data from each station were first averaged across all depths to get a station average. Station data were used to calculate a water quality summary (averages, maxima, minima, standard deviations) for the Territory, and station averages were regressed against station depth to evaluate potential spatial gradients. Beyond the basic statistical summary, we further evaluated these data using methods similar to those used for other coastal surveys (e.g., Macauley et al. 2002). In this case, data were assessed using the 2005 ASWQS outlined by the American Samoa Code Annotated (ASCA) for the appropriate coastal environments (Table 1). Most stations were classified as Open Coastal Waters. One station (#8), however, was located within the boundaries of Pago Pago Harbor; the specific harbor water quality standards were applied to that site's data only. For each parameter listed in Table 1, the station average was compared directly to each standard; if the value exceeded, was below, or was outside the range of the standard (depending on the standard), the station was considered out of compliance (i.e., 'fail'). For each parameter, the percent area (±95% CI) of the coastal waters that complied or failed to comply (or could not be evaluated) relative to the ASWQS was calculated.

Of the evaluated parameters, water clarity requires special explanation. Water clarity is an important component of coastal water quality (Smith et al. 2006), and the ASWQS require that light penetrate coastal waters to a certain depth (19.8 m within Pago Pago Harbor, 39.6 m in open coastal areas; Table 1). In order to evaluate whether water clarity was sufficient for light penetration to the specified depth (assuming each station was that deep), we calculated the light extinction coefficient that would allow 1% light penetration at the required depth. We next calculated the necessary percent transmission at the bottom of each station that would leave 1% light at the required depth. This number was compared to the calculated percent transmission. If the measured value exceeded the estimated value, then the station met

Table 1 Water quality standards adopted by the American Samoa Government and used by the American Samoa Environmental Protection Agency to evaluate marine waters

Parameter	Pago Pago Harbor	Open coastal
Total P (mg/L)	0.03	0.015
Total N (mg/L)	0.2	0.13
Chlorophyll (μg/L)	1	0.25
Light penetration (ft)	65	130
DO (mg/L)	5.0	5.5
pH	6.5–8.6	6.5–8.6
Enterococcus (CFU/100 mL MPN)	104	124

AS water clarity requirements (that is, light would reach the target depth). If the measured value was less than the estimated value, the site failed.

Results

Water quality summary

Of the 50 target sites (Figs. 1 and 2), we collected data from 49 stations; no water quality data were collected at station #41. Across all stations, depth averaged 14 m, with the maximum and the minimum depths being 38 and 0.15 m, respectively. Over 90% (46 of 49) of stations sampled were 25 m or less in depth.

The overall averages, maxima, minima, and standard deviations were calculated across the 49 sampled stations for each parameter (Table 2). With respect to the parameters evaluated using the numeric criteria, station DO levels in coastal waters were good, averaging 7.17 mg/L and never going below 6.5 mg/L. PH averaged 8.01. Chl *a* averaged 0.22 μg/L, but the highest station value was 0.60 μg/L. The station average for *Enterococcus* was 0.4 CFU/100 mL (MPN); the highest value was 3.3 CFU/100 mL (MPN). Station averages for TN and TP were 0.111 and 0.012 mg/L, respectively. The highest TN value for any station was 0.149 mg/L; the highest TP value, 0.016 mg/L.

For the other parameters for which there is no standard, average station TSS was 3.16 mg/L. DIN averaged 0.0122 mg/L, ranging from 0.0065 to 0.0265 mg/L. Nitrate was generally the largest fraction of the DIN (comprising approximately 50%) in these coastal waters. But overall, the fraction of dissolved inorganic nitrogen compared to the total nitrogen in the water was low, averaging only 11.1% and comprising at most 28% of the total N pool. Urea, the only measured organic N constituent, was similarly low, typically equaling the DIN total at each station. DIP averaged 0.012 mg/L across all stations. Furthermore, the DIP fraction was nearly 100% of the TP pool across all stations. These data indicate that the majority of nitrogen in marine waters around American Samoa is organic while the majority of phosphorus in those same coastal waters is inorganic.

For most measured parameters, there was no relationship between the average water column measurement and the station depth. However, a few parameters showed significant relationships with station depth, which suggests that there may be gradients from shore. Both DO and pH were higher at shallower stations. DO in particular was highest (between 8–10 mg/L) at stations that were <2 m deep. Furthermore, there was a significant relationship between the average DIN concentration and the station depth (Fig. 3), implying a significant DIN concentration gradient from shore.

Table 2 Water quality averages, maximum and minimum values, and standard deviations from data collected at 49 stations around the main islands of American Samoa

Parameter	Average	Maximum	Minimum	St. dev.
Temperature (°C)	28.8	29.8	27.6	0.8
Sal (ppt)	35.9	36.7	34.9	0.4
pH	8.01	8.23	7.6	0.17
DO (mg/L)	7.17	9.87	6.50	0.81
Chl *a* (μg/L)	0.22	0.60	0.07	0.14
TN (mg/L)	0.111	0.149	0.073	0.018
TP (mg/L)	0.012	0.016	0.008	0.002
***Enterococcus* (MPN)**	0.40	3.33	0	1.10
Nitrate (mg/L)	0.006	0.013	0.003	0.002
Nitrite (mg/L)	0.002	0.005	0.000	0.001
Nitrate + Nitrite (mg/L)	0.008	0.015	0.005	0.002
Ammonium (mg/L)	0.005	0.017	0.001	0.004
DIN (mg/L)	0.012	0.027	0.006	0.004
Urea (mg/L)	0.011	0.022	0.007	0.003
DIP (mg/L)	0.012	0.017	0.010	0.001
Silicate (mg/L)	0.105	0.505	0.047	0.064
TSS (mg/L)	3.16	5.33	1.08	0.88

Parameters for which there are ASEPA standards are bolded

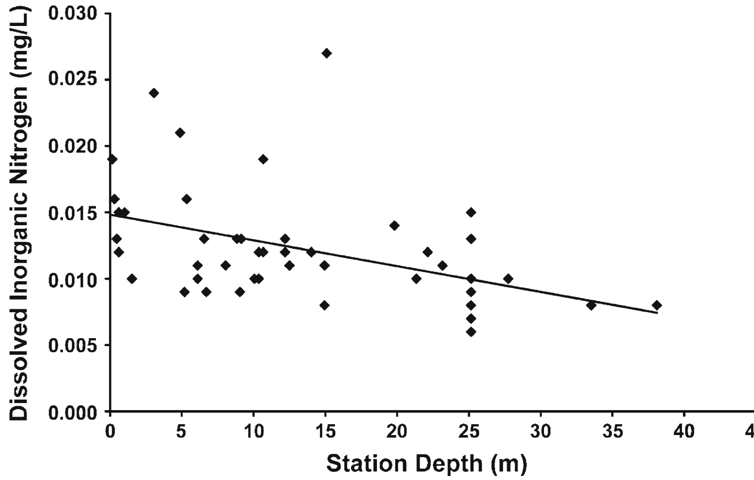

Fig. 3 Linear relationship between station depth (m) and the concentration (mg/L) of dissolved inorganic nitrogen (DIN) in near-shore waters around the high islands of American Samoa ($R^2 = 0.2084$; $p = 0.001$)

Coastal water quality assessment

The results of the assessments using the Territorial water quality standards are presented in Table 3. All station pH values were within the required range for Territorial waters. All station DO measurements complied with the Territorial standard, although there were several stations where DO data were missing. In total, this assessment found that 81 ± 15% of the Territory's near-shore coastal areas complied with the DO standard. Similarly, all *Enterococcus* samples collected around Tutuila and Aunu'u, representing 64 ± 18% of Territorial near-shore waters, complied with the Territorial criteria. With respect to the Chl *a* standard, 66 ± 18% of the Territory's waters complied with the standard, while 34 ± 18% failed to comply with the standard. For water clarity, 54 ± 18% of the coastal waters complied with the standard while 42 ± 7% failed to comply. Clarity data were missing for the remaining 4% of Territorial waters. Of the 13 sites that failed to meet the Chl *a* standard and the 20 stations that failed to meet the clarity standard, only five of those stations failed to meet both, implying that high Chl *a* is not generally the cause of reduced water clarity. However, total suspended solids (TSS) for waters that failed the clarity standard (3.45 ± 0.22 mg/L) was higher than TSS at stations that satisfied the clarity standard (2.99 ± 0.16 mg/L), implying that TSS may be a significant factor in water clarity at the station level and may be a significant problem Territory-wide. Water column nutrient status was assessed using TN and TP criteria. For Territorial waters, 72 ± 17% complied with the TN standard, while 21 ± 10% failed to comply with the standard. In addition, 92 ± 10% complied with the TP standard, while 1 ± 10% failed to comply with the standard. Approximately 7% of the Territory could not be assessed for either TN or TP.

Table 3 Results from the assessment of American Samoa's coastal water quality

Parameter	Pass	Fail	Not assessed
Total P (mg/L)	92 ± 10%	1 ± 10%	7%
Total N (mg/L)	72 ± 17%	21 ± 10%	7%
Chlorophyll (μg/L)	66 ± 18%	34 ± 18%	
Light penetration (feet)	54 ± 18%	42 ± 7%	4%
DO (%sat, mg/L)	81 ± 15%		19%
pH	100%		
Enterococcus (MPN)	64 ± 18%		36%

Percent area (±95% CI) of Territorial waters corresponding to each outcome (pass/fail) was calculated. In the case of missing data, the percent area that could not be assessed is listed

Discussion

This study is the first broad-scale investigation of water quality in the near-shore coastal areas around the main islands of American Samoa. Up to this point, there has been intensive study of Pago Pago Harbor, and piecemeal investigations concerning water quality, coral reef community dynamics (Dahl 1981; Green et al. 1999; Cornish and DiDonato 2004; Houk et al. 2005), and fish populations (Craig 1996) in parts of the Territory. Our objectives for this study were to collect water quality data and use those data to assess the current condition of the Territory with respect to local water quality standards. The probabilistic sample design provided a Territorial assessment based on information collected from a limited number of randomly located stations.

Craig et al. (2000), citing local documents, reported that coastal waters around American Samoa generally met local water quality standards, and Craig et al. (2005), in the absence of new information, reiterated this conclusion. Data collected as part of this survey corroborated that opinion for some of the indicators. Most of the Territory satisfied the water quality standards for hydrographic parameters (DO, pH); furthermore, all *Enterococcus* samples were well within the single sample limit proposed to indicate waters safe for body contact recreation. TP only exceeded the standard three times out of 49, suggesting that only 1% of the Territorial coastal waters are impaired for that nutrient (Table 3).

On the other hand, this survey demonstrated that three water quality indicators (water clarity, Chl *a*, and TN) frequently violated the Territorial standards, suggesting potential water quality issues around these islands. Elevated Chl *a* levels could be indicative of localized eutrophication, which is often associated with increases in human population and nonpoint source pollution. These survey data also suggest that reduced water clarity could be related to TSS, possibly associated with land use changes.

While these data are mixed with regards to Territorial water quality, they provide the first "big-picture" view of water quality in the near shore region around the high islands of American Samoa. While some specific Territorial locations have received attention from local and federal agencies (e.g., Pago Pago Inner Harbor; see Craig et al. 2000, 2005), this is the first territory-wide assessment. While good results were expected because of the connection to open ocean waters, these data indicate emerging water quality issues. Continued monitoring of near shore water quality is merited.

Another benefit of these data and, more specifically, this approach to coastal monitoring in the Territory is that these survey data can be used to evaluate overall condition of coastal waters and fulfill the Territory's 305(b) reporting requirements. Section 305(b) of the US Federal Clean Water Act requires States and Territories to assess the condition of water resources and document the programs used to evaluate aquatic resources. The National Coastal Assessment probabilistic design used here provided a means to survey coastal water quality and assess current status with known confidence. Instead of using data from specific embayments or particular areas of interest, this approach facilitated a comprehensive evaluation from randomly selected stations. Of particular value to the Territory was the fact that the survey design was used in conjunction with local water quality standards, those that had previously been adopted for the Territory and its unique coastal habitats.

In addition to the overall assessment, there were other interesting results from this survey. The American Samoa Water Quality Standards do not include specific criteria for either DIN or DIP; however, we examined these parameters for two reasons. First, as part of the National Coastal Assessment protocols, estimating DIN and DIP for American Samoa waters will facilitate later comparison with other tropical islands or regions. Second, these constituents are highly labile and rapidly utilized by marine phytoplankton and macroalgae; excessive quantities may indicate nutrient stress for the coral-dominated reefs. In the Caribbean, increased levels of DIN and DIP associated with anthropogenic impacts have been shown to facilitate a shift from hard coral communities to those dominated by macroalgae (Lapointe 1997; Lapointe et al. 2004).

In the coastal waters of American Samoa, DIP was the largest fraction of total phosphorus. In a survey of seven sites around Tutuila, Hansen et al. (2006) collected marine water quality data, and those data showed that DIP comprised on average 61% but up to 94% of the TP in marine waters. That result was consistent with our finding that DIP comprises a majority of the total phosphorus pool. Furthermore, these survey data demonstrated that DIP consistently exceeded a proposed nutrient threshold (PO_4: 0.1 μM; Lapointe 1997) for oligotrophic marine waters that, when exceeded, might indicate or portend nutrient-related reef degradation. In fact, all 49 sampled stations exceeded the 0.1 μM threshold for PO_4. These data suggest that source(s) of phosphorus may be natural (e.g. weathering of volcanic rock, seabird inputs). In fact, the stations with the highest TP (0.016 mg/L; stations #1, 2, and 4) were located along the central north shore of Tutuila (Fig. 1). Significant seabird populations are located there, and high phosphorus concentrations may reflect guano input. The effects on these marine ecosystems (e.g., coral reefs) of waters naturally high in DIP are unclear and may merit further study.

Contrary to DIP, the concentrations of DIN were typically low and made up only a small portion of the total nitrogen pool. Hansen et al. (2006) found similar ratios of inorganic to total nitrogen in their survey. Furthermore, only 11 of the 49 (22%) stations sampled in this survey exceeded the Lapointe (1997) threshold for DIN (1.0 μM). However, there was a DIN gradient demonstrating that shallower waters have higher concentrations of DIN than deeper waters (those further away from shore). This spatial gradient may be natural (e.g. driven by benthic pelagic coupling in shallow waters), but it also may be influenced by urbanization and land use changes in island watersheds. Preliminary evidence from a local stream survey showed that the nitrate concentration in stream water goes up as intact forests are converted to agriculture or urban land use (ASEPA, unpublished data). Freshwater input may indeed contribute this highly labile nutrient to coastal waters. It should be a significant concern to local resource managers that increasing inputs of nitrogen from anthropogenic activities, in the presence of high levels of DIP, could influence productivity and increase the likelihood of a shift in near-shore reefs from hard corals to macroalgae (Lapointe et al. 2004).

In conclusion, the unique coastal habitats of American Samoa, including the coral reefs, are threatened by pollution from land-based anthropogenic activities (Craig et al. 2005; Kelty and Kuartei 2005). The assessment reported here afforded the first quantitative “big-picture” view of water quality around those islands. While several measured parameters satisfied the local water quality standards, data indicated potential problems with respect to water clarity, Chl *a*, and TN and refuted the notion that coastal water quality can be assumed to be good. For local managers, the results suggest that land-based sources of pollution are having an impact on the water quality of the coastal waters. Elevated nutrients and suspended sediments may be responsible for localized eutrophication and reduced water clarity, respectively. Renewed emphasis on management programs, including education and outreach, is warranted. Furthermore, the results of this comprehensive survey, because it targeted and assessed the larger Territory, could lead to a better understanding of coastal water quality issues and concerns.

Acknowledgements D. Neighbor, T. Tasi, L. Fuamatu, and F. Tuilagi (National Park of American Samoa) provided institutional support for this project, and J. Macauley (USEPA) provided invaluable logistical support. P. Bourgeois (USGS) provided the study design and mapping-related assistance. P. Peshut and E. Buchan (American Samoa Environmental Protection Agency) and C. Goldstein (USEPA) provided necessary laboratory space and resources. I. Vaouli, J. Kim, and A. Tago (ASEPA) analyzed bacteria samples and assisted in field collections. Lance Smith (UH) assisted with field work in Manu’a. The manuscript was improved by the comments of two anonymous reviewers.

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