HEAVY METALS IN BIOTIC REPRESENTATIVES FROM THE INTERTIDAL ZONE AND NEARSHORE WATERS OF TANAPAG LAGOON, SAIPAN, COMMONWEALTH OF THE NORTHERN MARIANA ISLANDS (CNMI)

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WATER AND ENVIRONMENTAL RESEARCH INSTITUTE
OF THE WESTERN PACIFIC
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Plate 1: View of beautiful Tanapag Lagoon, Saipan, looking southwest from Suicide Cliff in the northern part of the island

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Plate 2: Local fisherman catches small, juvenile fish from the shallows of Tanapag Lagoon, Saipan, using a cast-net or ‘talaya.’

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ABSTRACT

Tanapag Lagoon borders the western shore of central Saipan. It harbors a rich diversity of marine life and supports a variety of commercial and recreational activities. Over the last quarter century, Tanapag Lagoon has become heavily impacted by the activities of man. Primary sources of anthropogenic disturbance in these waters include a power station and commercial port (Saipan Harbor), two small boat marinas, a sewer outfall, several garment factories, auto and boat repair shops, wood shops, government vehicle maintenance yards, a commercial laundry, and an acetylene gas producer. There are also a number of old military dumps and disposal sites in the area as well as a municipal dump that served as the island's only solid waste disposal site for over 50 years before its gates were permanently closed in February, 2003[1]. Several streams and storm drains empty into the lagoon during the rainy season and provide a mode of transport into the ocean for any land-based contaminants. Overflows from sewer lines are also commonplace at this time of the year and the whole area is inundated by storm water runoff during periods of prolonged wet weather. The effects of these perturbations on the indigenous biota within the lagoon are largely unknown. Likewise, fundamental data describing the abundance and distribution of persistent and potentially toxic pollutants within the system is also lacking. Mindful of these shortcomings, a contaminant assessment of surface sediments within Tanapag Lagoon was completed in 2001 and identified significant metal enrichment in the southern half of the lagoon, particularly around the dump. The study described herein examined trace metal levels in biotic components within the lagoon and was seen as a logical extension of the work already completed. Sampling was conducted in June 2003 and focused on a suit of dominant ecological representatives (algae, seagrass, seacucumbers, bivalves and juvenile fish) and intertidal sediments collected from 12 sites along the coast between Micro Beach (Garapan), at the southern end of the lagoon, and Pau Pau Beach Park (San Roque) in the north. These representatives included species with known or suspected bioindicator potential as well as those popularly harvested for human consumption.

The study confirmed previous findings of trace metal enrichment in surface sediments around the base of the Puerto Rico Dump. Levels of copper, lead and zinc measured here were at least two orders of magnitude higher than the lowest values determined elsewhere in the lagoon, while values for cadmium, chromium, mercury and nickel were at least one order of magnitude higher. It also clearly demonstrated that this enrichment is being transmitted to biotic components in the area although the implications from the data are that natural processes operating in the sediments and overlying water column place some constraints on rates of transfer. Significant copper, lead and zinc enrichment was identified at Echo Bay, Seaplane Ramps and CUC Beach. Overall the findings reflected inter-specific differences in bioindicator capabilities of the organisms analyzed as well as inter-site differences in the sources, abundances and biological availabilities of trace metals in the sediments and overlying water column. All bivalves collected close to the dump exceeded the current US FDA non enforceable guidelines for Pb in shellfish, and several international standards for Cu in fish and fisheries products. Trace metal levels in the edible tissues of all other organisms sampled within the lagoon were all well below critical threshold levels of concern.

[1] Remediation strategies for this now overgrown facility have yet to be implemented

INTRODUCTION

Tanapag Lagoon is a typical high-island barrier reef lagoon bordering the western shore of central Saipan. It is approximately 9 km long, 3 km at its widest point, and covers an area of around 13 km^2. Large expanses of patch reef interspersed with sand and rubble provide for a diversity of shallow water habitats and harbor rich assemblages of flora and fauna (Doty and Marsh 1977, Amesbury *et al.* 1979). In addition to its ecological significance, the lagoon supports a variety of recreational activities and local people traditionally harvest many of its fisheries resources for food. Protecting and preserving this environment and its resources for future generations is therefore very important to the people of Saipan.

Prior to the last world war, Saipan was essentially a small, rural community, free of the environmental pressures seen on the island today. Sources of pollution were minimal and largely associated with the disposal of domestic wastes from small settlements dotted around the coast. As a result, Saipan's coastal waters were in relatively pristine condition. Today, things are somewhat different, particularly on the western side of the island where the bulk of the population now exists. This area has undergone considerable urban growth and economic expansion in recent years. Such development has, in turn, greatly added to the waste disposal, urban runoff, chemical pollution and environmental management problems that the island currently has to deal with.

In contrast to pre WWII days, much of the coastline bordering the Tanapag Lagoon now supports a variety of commercial and industrial facilities. These include a major sea port (Saipan Harbor), two marinas, the largest power plant on island, a five-star hotel, several large garment factories, auto and boat repair shops, wood shops, government vehicle maintenance yards, a commercial laundry, and an acetylene gas producer. Wastes from many of these establishments are largely uncontained and uncharacterized, and in certain cases are either dumped on the business premises or piped directly into the environment. A number of freshwater streams flow into the lagoon during the wet season and provide a mode of transport for such land-based contaminants into the ocean. The same can be said for the stormwater runoff that inundates the coastal belt during prolonged periods of wet weather. It is noteworthy that overflows from sewer lines are also commonplace at such times.

Other notable sources of contamination along this section of coastline include remnants of wrecked military vehicles and landing craft plus a number of unexploded ordnances scattered along the beach between the villages of San Roque and Tanapag in the northern half of the lagoon. Further south, in the Lower Base area, is a large junkyard and a government storage area for old lead-acid batteries and waste-oil. Both of these facilities are within 100 meters of the beach. Saipan Harbor, at the southern end of the lagoon, is also the sight of a bulk fuel holding facility and abuts onto the Puerto Rico Dump, a 20-acre facility that spills into the water. The dump served as the island's primary solid waste disposal site for over 50 years before its gates were officially closed in February 2003 and is rumored to contain a plethora of toxic chemicals of both military and civilian origin (Ogden 1994). A sewage outfall, located approximately 500 meters offshore from the Harbor docks, delivers around 3-5 million gallons of secondary treated effluent into the lagoon each day.

Given the numerous sources of pollution identified above, there is little doubt that subtle changes in water quality have occurred throughout Tanapag Lagoon over the last few decades. However, to what extent such changes have altered the delicate ecological balance of this environmentally sensitive area is currently unknown. Likewise, there have been relatively few attempts to identify chemical contaminants of primary concern and monitor their distribution and abundance within abiotic and biotic components of the lagoon. In fact, only two such studies have so far been reported. The first of these was undertaken in the late 1980s by the CNMI Division of Environmental Quality (DEQ 1987) and evolved out of concern over the possible impact of the Puerto Rico Dump on the immediate marine environment. It was conducted with technical assistance from USEPA (Region IX) and involved the chemical analysis of water, sediments and fish from shallow water sites on the seaward side of the dump. Both sediments and fish were found to be relatively enriched with a variety of heavy metals, hardly surprising considering the diversity of industrial uses of transition elements in the world today (Table 1).

Despite the many analytical and sampling shortcomings associated with this work, the information obtained represented a significant milestone in Saipan's water quality database by providing the first definitive evidence that chemical imbalances and abnormalities were indeed occurring in the island's coastal waters. It also emphasized the need for a more comprehensive evaluation of the situation in order to understand the full impact of mans intrusion into this fragile environment.

The second study, undertaken in June 1999 was far more ambitious and set out to determine the distribution and abundance of heavy metals, PCBs and PAHs in surface sediments from the southern half of Tanapag Lagoon where the majority of commercial and industrial activities are centered. Both nearshore and offshore sampling sites were included in this study with emphasis on areas adjacent to known pollution sources such as a power plant, the Puerto Rico Dump, Saipan Harbor, two small boat marinas and a sewer outfall. Not surprisingly, areas of heavy metal enrichment were identified in sediments close to all of these places (Denton *et al*. 2001, 2006a).

Determining the overall impact of such enrichment on biotic components within the lagoon is a necessary component of any program directed towards the sustainable development of fisheries resources in these waters and is seen as a logical extension of the earlier works. The development of such a database is also an essential prerequisite for any long-term monitoring activities planned for the area and provides the necessary benchmarks against which future findings may be compared and evaluated.

In recognition of these needs, a baseline survey of heavy metals in dominant ecological representatives within the lagoon was recently undertaken. The study reported herein presents data for arsenic (As), silver (Ag), cadmium (Cd), chromium (Cr), copper (Cu), mercury (Hg), nickel (Ni), lead (Pb) and zinc (Zn) in common species of algae, seagrass, seacucumbers, bivalve mollusks and juvenile fish (arsenic and mercury only) inhabiting the intertidal and nearshore waters of Tanapag Lagoon. The suit of organisms selected for study included several with known or suspected bioindicator capability. A number of these are also popularly consumed by island residents. Thus the study has special significance from a human health standpoint.

Table 1: Past and Present Industrial Uses of the Heavy Metals Examined[a]

Metal	Uses of Metals and Metal Compounds[b]
Arsenic:	Component of pesticides; wood preservative; alloys; semi-conductors; medicines; glass and enamels.
Cadmium:	Electroplating (anticorrosion coatings); thermoplastic stabilizers, e.g. in PVC; Ni-Cd batteries; alloys; solders; catalysts; engraving; semi-conductors; TV tube phosphors; pigments in paints and plastics; glass ceramics; biocides
Chromium:	Metallurgy—ferrochromium alloys; refractory bricks; electroplating; industrial dyes; ink; tanning; paint; wood preservative; glass making; cement production.
Copper:	Electrical industry; alloys; e.g. brass; chemical catalyst; anti-fouling paint; algaecide; wood preservative.
Lead:	Storage batteries; leaded gasoline; pigments; red lead paint; ammunition; solder; cable covering; anti-fouling paint; glazing; PVC stabilizers.
Mercury:	Chlorine production; electrical apparatus; anti-mildew paint; instruments; catalyst e.g. for PVC and acetaldehyde production; pesticides; preservatives; pharmaceuticals; dentistry; anti-fouling paint.
Nickel:	Metallurgy—steel and other alloys; electroplating; catalyst; rechargeable Ni-Cd batteries.
Silver	Photography; electric conductors; sterling ware; solders; coinage; electroplating; catalyst; batteries; food and beverage processing.
Zinc	Zinc based alloys; brass and bronze; galvanizing; rolled zinc; paints; batteries; rubber; sacrificial anodes on marine water-craft.

[a] from Bryan (1976), Förstner and Wittmann (1981), Moore (1991), Bryan and Langston (1992)
[b] importance generally decreasing from left to right.

MATERIALS AND METHODS

GENERAL DESCRIPTION OF STUDY AREA

Twelve sampling sites were selected between Micro Beach at the southern end of the Tanapag Lagoon and San Roque village in the north (Figure 1). Important considerations that determined the location of each site included accessibility, species availability and proximity to potential land-based sources of contamination. Sampling sites in the southern half of the lagoon were generally closer to commercial activities and industrial discharges than sites further north. A brief description and photographic record (Figure 2) of each site is given below.

Micro Beach (Site 1):

Micro Beach is a relatively high energy beach that borders the American Memorial Park in the village of Garapan. Intertidal sediments are predominantly composed of very coarse, clean carbonate sands of biogenic origin. These give way to finer deposits immediately offshore. The area receives some seasonal drainage from the park and tidal flushings from Smiling Cove Marina. Additionally, the net southerly movement of surface water currents along the coast transports aqueous contaminants into the area from the port (Saipan Harbor) and the Puerto Rico Dump immediately to the north. Site 1 was located at the northern end of Micro Beach near the marina entrance.

Puerto Rico Dump (Site 2):

Site 2 was located along the south western edge of the dump in a relatively low energy environment. Sediments in this area were predominantly composed of poorly sorted, gravelly coarse sand interspersed with muddy fines of marine and terrestrial origin, metal fragments, glass, wood, plastic, cloth fibers, bituminous asphalt, rubber and tar balls. Aqueous contaminants impacting this site are principally derived from the dump itself (in leachate streams), the port, and surface water drainage from Industrial Drive, a short stretch of road that provides access to various commercial activities in the immediate area.

Echo Bay (Site 3):

Poorly sorted medium to coarse carbonate sands of biogenic origin occur throughout much of this relatively sheltered bay that separates the main Port on the western side from Echo docks on the east. Primary source of contamination in this area are associated with shipping activities, including boat repair and maintenance. Site 3 was located at the western end of the bay near a small stream that drains an area of nearby wetland. The stream is locally known as Saddok Tasi, and also receives drainage from a portion of Lower Base Drive and Middle Road.

Seaplane Ramps (Site 4)

As its name suggests, this twin ramp facility was built to accommodate seaplane transportation at the end of WWII. Today, the most western ramp serves as a jetty for tour boat operators while the eastern ramp is used primarily for dry dock boat maintenance. Sediments in the intertidal zone between the two ramps are typically very course, gravelly sand, while finer deposits occur in deeper waters along side the ramps themselves. Site 4 was centrally located on the inner side of the eastern ramp. Primary sources of contamination in this area are almost exclusively confined to shipping and ship repair activities.

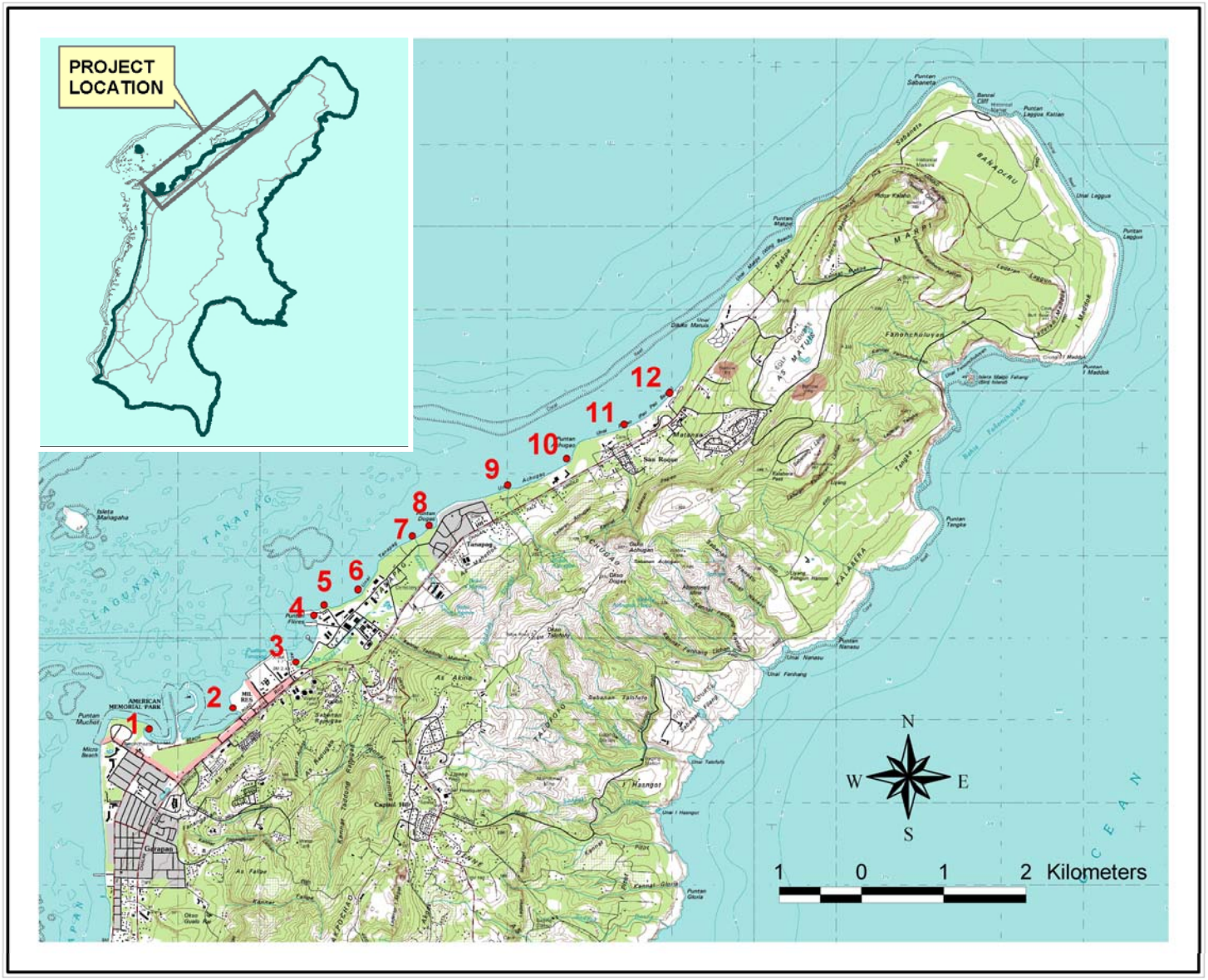

Figure 1: Biota and sediment sampling site locations in Tanapag Lagoon, Saipan

Site 1: Micro Beach (northern end)

Site 2: Puerto Rico Dump (southwest side)

Site 3: Echo Bay (western end)

Site 4: Sea Plane Ramps (eastern ramp)

Site 5: CUC Beach (looking north)

Site 6: Lower Base Channel

Plate 3: Intertidal and shallow water sampling sites 1-6 in Tanapag Lagoon, Saipan

Site 7: Saddok As Agatan

Site 8: Saddok Dogas

Site 9: Bobo Achugao

Site 10: Plumaria Hotel Beach

Site 11: San Roque Cemetery Beach

Site 12: Pau Pau Beach

Plate 4: Intertidal and shallow water sampling sites 7-12 in Tanapag Lagoon, Saipan.

CUC Beach (Site 5):
CUC beach as it is popularly referred to is a stretch of boulder strewn beach that lies immediately to the east of the Lower Base power station and was the location of Site 5. Sediments at this site were predominantly composed of fine to medium biogenic sands interspersed with muddy fines of mixed origin. The site borders a Department of Public Works vehicle maintenance yard and an open are of land previously used as a dumpsite for old car batteries and other assorted automobile hardware. A metallic waste recycling facility is located close by on Lower Base Drive although no obvious surface water drainage pathways to the coast are present in the area.

Lower Base Channel (Site 6):
This unnamed section of beach receives discharge from a small creek that drains the Lower Base area. Over time, the creek has cut a conspicuous channel through the fine to medium muddy sands that predominate here. Urban runoff and industrial activities along the Lower Base Drive are the primary sources of heavy metal contamination in this area.

Saddok As Agatan (Site 7):
Saddok As Agatan is the largest of three streams that drain watersheds of the hilly interior in this part of the island. It discharges continuously onto a relatively flat beach approximately 300 m southwest of Tanapag village. Sediment characteristics ranged from relatively course sand in the upper intertidal zone to finer, muddier material further offshore. No obvious sources of heavy contamination were evident in the area.

Saddok Dogas (Site 8):
Saddok Dogas, the second stream in this area, empties onto the beach approximately 150 m from the southern boarder of Tanapag village. The sediment characteristics here were generally the same as described for the preceding site. The stream drains an upland area of land that was once used as a military dumpsite and an array of military junk can still be found in one of the headwater tributaries. No other obvious sources of heavy contamination were evident in the area.

Bobo Achgao (Site 9):
Bobo Achagao is the smallest of the three streams that discharge into this area of coastline and is the first to stop flowing during prolonged periods of dry weather. The mouth of the stream was characterized by small but a well defined delta of coarse aggregate interspersed with medium to fine sand. The latter materials predominated throughout the intertidal and sub tidal regions of the beach flat at this site.

Plumaria Hotel Beach (Site 10):
Clean, coarse sands characterized the intertidal zone of this relatively pristine, shallow water embayment. Somewhat finer deposits of clean sand were found sub tidally. Other than the hotel, there were no obvious potential sources of heavy metal contamination in the area. Site 10 was located at the northern end of the embayment and was considered to be representative of a relatively pristine stretch of coastline.

San Roque Cemetery Beach (Site 11):
Bordering the San Roque cemetery, beach sediments at this location were similar to those of the preceding site. The site was selected for study because it received effluent from a nearby reverse osmosis desalination plant at the Nikko hotel.

Pau Pau Beach (Site 12):

This popular beach park area was the northern most collection site visited during the present study. Relatively high energy conditions prevail along this narrow stretch of Tanapag Lagoon giving rise to clean coarse to very coarse sediments with little terrigenous material present. Sources of heavy contamination in the area include storm water drainage from the main highway and septic tank seepage from the public restrooms.

SAMPLE COLLECTION AND PREPARATION

All samples for heavy metal analysis were collected over a two week period in June 2003. Surface sediment samples (~100 g) were taken from the intertidal region of each beach site. They were gently scooped up in acid washed plastic containers so as not to disturb surface layers. In the laboratory, all samples were dried at either ~30^{o}C (for mercury analysis) or ~60^{o}C (for all other metals) and sieved through a 1-mm Teflon screen in preparation for analysis. Sediment characteristics varied appreciably between sites with cleaner coarser materials generally predominating in the intertidal and immediate subtidal zones of the northern half of the lagoon.

Biota were collected on low and falling tides with emphasis on species with established or potential bioindicator capability as well as those traditionally harvested by local residents for food (Plates 4-6). Organisms within the former category provide a useful means of determining changes in metal availability within the aquatic environment (Phillips 1980). Candidate species are usually sessile, or are restricted in their movement, and demonstrate little if any metabolic control over tissue levels of the heavy metals of interest to the investigator. Organisms fulfilling these essential prerequisites thus tend to mirror biologically available amounts of heavy metals derived from their immediate surroundings. Algae and bivalve mollusks generally have poor regulatory capacity for heavy metals and consequently have high bioindicator potential. Fish, on the other hand, exhibit some metabolic control over most heavy metals with the notable exception of mercury. The selection of appropriate organism is therefore of paramount importance if meaningful interpretations are to be had from the data obtained. A complete list of the organisms taken for analysis, together with their respective collection sites, is shown in Table 2. Not all species were available at all sites. This was largely attributed to substrate variability along the coast.

The juvenile fish were captured using a cast net and immediately placed in chilled containers. Bivalve mollusks were recovered from beach sediments using a small metal rake and trowel and transported to the laboratory in plastic buckets filled with seawater. All other specimens collected were handpicked from the lower intertidal and sub tidal zones at each site and transported to the lab in clean polyethylene bags. Gross particulate material was rinsed from the algae beforehand by vigorously shaking the samples back and forth in clean seawater; the holdfasts and older, more encrusted portions of the plants were discarded. Blades of seagrass were carefully removed as close to the plant root as possible. The proximal 12 inches of each blade was relatively free of epiphytic growth and the only portion of the plant taken for analysis. Bivalves were scrubbed clean of adhering particulates and purged of their gut contents in clean seawater for 48 h prior to freezing. Subsequently, the entire soft parts of thawed specimens were taken for analysis. In contrast, seacucumbers were dissected live to prevent tissue fluid cross-contamination that can occur during the thawing of frozen specimens. Dorsal sections of the body wall and the portions of the hemal system were separated out for analysis from these organisms. Axial muscle was taken for analysis from pooled samples of thawed juvenile fish. Pool sizes generally ranged from one to six fish depending upon the species and size if individuals caught.

All cleaned and separated biota samples were placed in acid-washed, polypropylene vials (80 ml) and stored at -20^{o}C until required for analysis. The analyses were performed on samples dried to constant weight at 60^{o}C for all metals except arsenic and mercury. Owing to the relatively high volatility of these elements the analysis was conducted on wet rather than dried tissues.

SEDIMENT ANALYSES:

All samples were analyzed for heavy metals by atomic absorption spectroscopy (AAS) following conventional wet oxidation in hot mineral acids. This digestion procedure is essentially similar to EPA method 3050A, SW-846 (USEPA 1995) with minor modifications as outlined below. It is designed specifically to release weakly to strongly bound metals in the sample without completely destroying the non-carbonate, mineral matrix of the sample and is particularly useful for identifying metal enrichment as a result of anthropogenic activities.

Table 2: Flora and Fauna Sampled During the Present Survey

Species	Sites											
	1	2	3	4	5	6	7	8	9	10	11	12
ALGAE:												
Acanthophora spicifera	x			x			x	x	x	x		
Dictyota bartayresiana											x	
Gracilaria salicornia		x	x		x	x			x			
***Laurencia* sp.**		x	x									
***Padina* sp.**		x	x	x			x		x	x	x	x
Sargassum polycystum											x	
SEAGRASS:												
Enhalus acaroides	x	x		x	x	x	x	x	x			
Halodule uninervis					x				x	x	x	
SEA CUCUMBERS:												
Bohadschia argus								x				
Bohadschia mormorata			x	x	x	x						
Holothuria atra	x	x	x	x	x	x	x	x	x	x	x	x
BIVALVES:												
Asaphia violascens		x										
Atactodea striata	x							x	x	x	x	x
Ctena bella	x											
Gafrarium pectinatum		x	x		x	x						
Pinna fragilis						x						
Quidnipagus palatum		x	x		x	x						
JUVENILE FISH::												
Caranx sexfasciatus	x	x		x		x	x					
Gerres argyreus	x	x	x	x	x	x	x	x				
Mulloides vanicolensis	x	x	x	x		x	x	x	x	x	x	x
Valamugil engeli	x	x	x	x	x	x						

Arsenic and Mercury:

Approximately 5 g of sieved sediment samples were weighed into 80-ml polypropylene digestion tubes specifically made for a MOD BLOCK digestion block (CPI International). The tubes were loosely capped with Teflon stoppers and refluxed with 15-20 ml of concentrated nitric acid at 100^{o}C for 3 hours. Upon cooling the digests were topped up to 50 ml with distilled water ready for analysis. Arsenic analysis was accomplished by the hydride generation technique whereby inorganic arsenic is converted to arsine gas (AsH_3) by reduction with 3% sodium borohydride in 1% sodium hydroxide. Calibration standards (1-10 μg/l) for this element were made up in 10% nitric acid. Mercury was analyzed by flameless (cold vapor) atomic absorption spectrophotometry (AAS) and involved the generation of metallic mercury vapor (Hg^{o}) following reduction with 2% stannous chloride (Hatch and Ott 1968). The process was facilitated using the syringe technique described by Stainton (1971). All calibration standards (5-20 ng/l) for mercury were made up in 10% nitric acid containing 0.05% potassium dichromate as a preservative (Feldman 1974).

Other Metals:

Approximately 1 g of the dried sediment samples were weighed into 80 ml glass tubes and digested with approximately 10 ml of concentrated nitric acid at 110-135^{o}C for 3 hours in the apparatus described above. The digests were then evaporated to dryness and re-dissolved in 10 ml of 10% nitric acid with gentle warming. The contents of each flask was thoroughly mixed, allowed to stand for several minutes to permit settlement of residual particulates, and then decanted into clean polypropylene vials ready for analysis. Analysis was performed by flame AAS, the contents of each vial being aspirated directly into the instrument. Simultaneous corrections for non-atomic absorption were made by the instrument (deuterium lamp). All calibration standards (0.2-10 mg/l) were made up in 10% nitric acid from a commercial mixed stock solution (100 mg/l of each metal).

BIOTA ANALYSIS:

The procedures for biota analyses were essentially the same as those described for sediments with three notable exceptions. First, all samples were cold digested overnight to minimize frothing during the initial warming phase. Second, samples for arsenic and mercury analyses were digested in 2:1 nitric and sulfuric acids rather than nitric acid alone. The more powerful oxidizing mixture was required for the complete destruction of organic matter in the wet tissues. Finally, samples for all other metals were subjected to two 3-hour digestion/drying cycles with hot nitric acid prior to topping up to final volume with 10% nitric acid.

QUALITY ASSURANCE AND QUALITY CONTROL (QA/QC):

All reagents used were analytical grade and all plastic and glassware were acid-washed and deionized water rinsed prior to use. Standard stock solutions were purchased from a commercial supplier. Approximately 10% of samples were run in duplicate and were accompanied by appropriate method blanks and matrix spikes. Heavy metal recoveries from certified standard reference materials (one soil and four biota) were within acceptable limits for all elements examined (Tables 3-4).

PRESENTATION OF DATA:

The tabulated data are preceded by notes that compare and contrast the current findings with the work of others on a metal-by-metal basis. Reference to comparable investigations in Guam and other tropical areas of the world are also included where appropriate. Much of this data has been tabulated in Table 5 at the end of the current section to facilitate ease of reference.

Table 3: Recovery of Heavy Metals (µg/g dry wt.) from a Soil Standard Reference Material

Metal	This Study		Certified Values	
	Mean	Range	Mean	Range
	PriorityPollutnT™/CLP Inorganic Soils **[Catalog N° PPS-46; Lot N° 242]**			
Arsenic	57.3	50.8 – 65.6	58.6	41.1 – 76.1
Cadmium	190	181 – 211	185	143 – 228
Chromium	41.4	37.3 – 44.6	50.7	35.7 – 65.7
Copper	60.1	53.6 – 68.9	63.6	52.1 – 75.1
Lead	54.6	45.2 – 61.9	56.6	43.1 – 70.1
Mercury	1.29	1.11 – 1.42	1.29	0.83 – 1.74
Nickel	75.4	61.6 – 85.1	75.4	59.0 – 91.7
Silver	153	142 – 169	149	110 – 188
Zinc	62.9	57.2 – 72.8	69.6	51.1 – 88.1

Table 4: Recovery of Heavy Metals (µg/g dry wt.) from Biota Standard Reference Materials

Metal	**Mean ± 95% Confidence Limits**		**Mean ± 95% Confidence Limits**	
	This Study	**Certified Values**	**This Study**	**Certified Values**
	Apple Leaves (SRM 1515)		**Bovine Liver (SRM 1577b)**	
Cadmium	0.03 ± 0.01	0.013 ± 0.002	0.49 ± 0.01	0.50 ± 0.03
Copper	5.20 ± 0.25	5.64 ± 0.24	143 ± 2.94	160 ± 8
Chromium	0.38 ± 0.096	0.3[a]	0.95 ± 0.13	-
Nickel	1.00 ± 0.08	0.91 ± 0.12	0.61 ± 0.15	-
Lead	0.38 ± 0.01	0.47 ± 0.02	0.14 ± 0.01	0.129 ± 0.004
Silver	0.05 ± 0.01	-	0.05 ± 0.01	0.039 ± 0.007
Zinc	12.8 ± 0.60	12.5 ± 0.03	116 ± 4.17	127 ± 16
	Marine Mussels (SRM 2974)		**Albacore Tuna (RM 50)**	
Arsenic	3.24 ± 0.41	7.4 ± 1.1	2.98 ± 0.1	3.3 ± 0.4
Mercury	0.156 ± 0.014	0.176 ± 0.013	1.01 ± 0.03	0.95 ± 0.1

[a]unconfirmed reference value only; dashes indicate no data

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Table 5: Heavy Metals in Similar and Related Species of Marine Organisms from Guam and Elsewhere

Species	Location	Metal (µg/g dry wt.)									Reference
		Ag	As[a]	Cd	Cr	Cu	Hg[b]	Ni	Pb	Zn	
ALGAE:											
Acanthophora spicifera	Tanapag Lagoon, Saipan	<0.08-0.51	0.53-1.13	<0.13-0.70	<0.26-1.54	2.88-30.5	1.86-10.2	1.78-2.52	0.49-8.14	17.6-130	This Study
Acanthophora spicifera	Pago Bay, Guam	all <0.27	0.20-1.55	<0.16-0.47	<0.21-1.88	1.22-3.03	1.09-2.83	3.05-5.20	0.31-1.36	3.36-8.04	Denton *et al.,* 2006b
Dictyota bartayresiana	Tanapag Lagoon, Saipan	<0.16	4.50	0.47	0.56	1.87	3.54	1.28	0.63	29.6	This Study
Dictyota sp.	N. Queensland coastal wateres, Australia	-	-	0.70	-	6.90	-	5.70	0.40	18.8	Burdon-Jones *et al.,* 1975
Dictyota sp.	Gt. Barrier Reef, Australia	-	-	0.36-0.36	-	2.4-3.0	-	2.0-2.5	<0.8-2.9	3.9-12.4	Denton & Burdon-Jones, 1986
Gracilaria salicornis	Tanapag Lagoon, Saipan	all <0.11	2.19-2.82	<0.07-0.20	<0.23-0.93	1.22-2.90	2.42-4.38	<0.19-0.52	<0.23-1.17	11.6-24.8	This Study
Gracilaria salicornia	Pago Bay, Guam	all <0.26	1.43-1.67	all <0.26	<0..25-1.15	0.98-1.17	1.74-3.48	<0.16-1.07	all <0.58	2.92-8.71	Denton *et al.,* 2006a
Gracilaria sp.	N. Queensland coastal wateres, Australia	all <0.2	-	<0.2-0.8	1.7-4.0	2.3-3.9	-	0.3-1.4	all <0.4	11.2-15.6	Burdon-Jones *et al.,* 1975
Laurencia sp.	Tanapag Lagoon, Saipan	0.18-0.24	0.18-3.24	0.44-0.78	1.12-1.62	4.15-11.3	2.91-6.8	2.39-2.66	3.16-4.27	39.4-54.6	This Study
Padina sp.	Tanapag Lagoon, Saipan	<0.10-0.29	3.56-12.3	<0.11-1.72	<0.30-1.43	1.30-25.3	1.74-6.33	0.88-1.65	<0.27-14.7	5.3-107	This Study
Padina sp.	Apra Harbor, Guam	all <0.10	5.8-38.1	0.2-0.5	1.3-3.0	2.6-36.6	7-26	1.1-3.2	2.6-6.5	45.1-192	Denton *et al.* 1999., 2006c
Padina sp.	Small boat marinas, Guam	<0.10-0.89	17.4-32.2	<0.1-0.26	0.68-14.1	1.53-27.2	<2.00-3.00	1.18-2.9	<0.25-8.07	11.0-78.3	Denton *et al.* 1999., 2006c
Padina sp.	Lizard Island, Great Barrier Reef	-	-	0.2	-	2.2	2	1.1	<0.74	5.9	Denton & Burdon-Jones, 1986
Padina australis	Gt. Barrier Reef, Australia	-	-	0.4-0.6	-	2.0-3.0	1-4	1.0-1.4	<0.9-5.0	3.8-9.5	Denton & Burdon-Jones, 1986
Padina boyana	Pago Bay, Guam	all <0.18	1.96-11.0	<0.15-0.32	<0.23-2.14	0.74-4.65	0.59-2.97	1.56-3.36	0.27-13.9	2.75-8.27	Denton *et al.,* 2006b
Padina commersonni	Singapore coastal waters	-	-	0.4-0.6	2.9-6.5	3.8-7.3	<10[c]	4.0-6.5	4.3-7.9	20.7-50.1	Bok & Keong, 1976
Padina gymnospora	Puerto Rico	-	-	-	-	nd	-	23.0-32.0	-	-	Stevenson & Ufret, 1966
Padina tenuis	Penang Island, Malaysia	-	-	7.1	25.6	5.7	1025[c]	-	17.1	45.5	Sivalingam, 1978; 1980
Padina tenuis	Townsville coastal waters, Australia	<0.1-0.4	-	0.2-1.4	1.4-10.0	1.4-5.1	-	0.7-8.4	<0.3-6.2	3.7-30	Burdon-Jones *et al.,* 1982
Padina tetrostromatica	Goa coastal waters, India	-	-	nd	-	3.2-7.9	-	8.0-18.3	3.0-28.3	4.5-11.7	Agadi *et al.,* 1978
Padina tetrostromatica	Goa coastal waters, India	-	4.8-12.6[d]	nd	-	8.7-20.1	-	nd	nd	20.2-31.5	Zingde *et al.,* 1976
Padina tetrostromatica	Townsville coastal waters, Australia	<0.1-0.4	-	0.2-1.2	1.6-9.9	2.0-11.1	-	0.9-4.0	1.1-4.9	5.5-25.7	Burdon-Jones *et al.,* 1982
Padina tetrostromatica	Townsville Harbor, Australia	<0.1-0.4	-	0.2-0.6	2.1-31.5	4.4-58.9	-	0.7-13.1	2.0-108	67.2-440	Burdon-Jones *et al.,* 1975, 1982
Sargassum polycystum	Tanapag Lagoon, Saipan	all <0.16	15.6-22.9	0.28-0.40	<0.31-0.57	1.27-1.47	0.45-0.88	0.81-1.08	0.45-0.51	12.6-15.9	This Study
Sargassum polycystum	Pago Bay, Guam	all <0.16	9.61-22.4	<0.15-0.29	0.60-2.66	0.92-2.79	1.72-3.61	1.48-5.01	<0.31-1.51	2.56-7.01	Denton *et al.,* 2006b
Sargassum conusum	Korean waters	-	-	1.6	-	7	-	-	5.8	14	Pak *et al.,* 1977
Sargassum cristafolium	Pago Bay, Guam	all <0.16	2.39-117	<0.15-0.31	<0.20-1.20	0.46-1.63	1.12-4.06	0.68-5.13	<0.19-2.99	0.76-4.83	Denton *et al.,* 2006b
Sargassum fulvellum	Korean waters	-	-	2.4-3.0	-	8-19	-	-	4.2-6.2	11-23	Pak *et al.,* 1977
Sargassum cgrevillei	Penang, Malaysia	-	-	6.4	-	5.2	-	-	5.2	15.5	Sivalingam, 1978
Sargassum horneri	Korean waters	-	-	1.7-2.7	-	9-25	-	-	6.7-8.9	28-61	Pak *et al.,* 1977
Sargassum pallidum	Vostok Bay, Sea of Japan	-	-	-	-	4.3	-	-	-	2.7	Saenko *et al.,* 1976
Sargassum pallidum	Pacific coastal waters	-	-	1.3-5.1	-	1.6-4.3	-	-	5.5-25.2	2.7-95.9	Khristoforova *et al.,* 1983
Sargassum sp.	N. Queensland coastal wateres, Australia	all <0.2	-	all <0.2	<0.4-3.1	2.2-3.1	-	<0.3-1.1	all <0.4	7.0-10.0	Burdon-Jones *et al.,* 1975
SEAGRASSES:											
Enhalus acoroides	Tanapag Lagoon, Saipan	all <0.20	0.03-0.19	0.15-0.60	<0.30-0.40	2.15-48.0	0.85-9.01	0.60-2.34	<0.22-2.05	20.0-33.0	This Study
Enhalus acoroides	Pago Bay, Guam	all <0.16	0.10-1.22	all <0.16	<0.15-0.64	0.74-5.73	1.13-3.56	1.26-4.26	<0.30-1.07	4.96-16.6	Denton *et al.,* 2006b
Halodule uninervis	Tanapag Lagoon, Saipan	all <0.20	0.07-0.54	0.29-0.66	<0.32-1.09	2.45-6.46	1.80-3.53	0.70-1.25	<0.32-1.09	21.1-35.8	This Study
Halodule uninervis	Cleveland Bay, Townsville, Australia	<0.3	-	0.5	1.6	2.7	-	0.7	7	11.0	Denton *et al.,* 1980
Halodule pinifolia	Lockhardt River, Cape York, Australia	0.1	-	1.1	2.3	7.7	-	4.9	3.6	26.0	Denton *et al.,* 1980
Halophila ovalis	Lockhardt River, Cape York, Australia	<0.2	-	0.5	1.0	9.0	-	1.7	1	67.0	Denton *et al.,* 1980
Zostera capricornia	Upstart Bay, N Queensland, Australia	<0.2	-	0.2	0.9	3.0	-	0.6	0.4	18.0	Denton *et al.,* 1980
Zostera capricornia	Shoalwater Bay, N. Queensland, Australia	<0.2	-	0.2	1.9	2.8	-	1.8	0.4	14.0	Denton *et al.,* 1980

[a] Arsenic concentrations as µg/g wet weight; [b] mercury concentrations as ng/g wet weight; [c] mercury concentrations as ng/g dry weight; [d] arsenic concentrations as µg/g dry weight; dashes indicate no data

Table 5 cont.: Heavy Metals in Similar and Related Species of Marine Organisms from Guam and Elsewhere

Species	Location	Metal (µg/g dry wt.)									Reference
		Ag	As[a]	Cd	Cr	Cu	Hg[b]	Ni	Pb	Zn	
SEACUCUMBERS[c]:											
Bohadschia argus (M)	Tanapag Lagoon, Saipan	<0.09	7.45	<0.09	<0.37	0.86	3.42	0.30	<0.14	15.9	This Study
Bohadschia argus (H)	Tanapag Lagoon, Saipan	<0.11	0.59	0.32	4.27	2.48	36.3	0.44	<0.36	44.2	This Study
Bohadschia argus (M)	Apra Harbor, Guam	all <0.13	7.8-17.7[d]	0.1-0.1	<0.2-0.4	0.6-2.3	5-5	1.0-1.4	<0.3-0.6	13.8-18.0	Denton *et al.* 1999., 2006c
Bohadschia argus (H)	Apra Harbor, Guam	all <0.14	16.6-32.6[d]	0.32-0.39	7.28-31.9	2.84-39.0	221-459	0.43-1.21	<0.33-0.88	41.4-374	Denton *et al.* 1999., 2006c
Bohadschia argus (M)	Small boat marinas, Guam	all <0.10	all <0.01[d]	0.10-0.10	<0.10-0.10	0.6-0.9	1-7	0.3-1.1	all <0.4	8.3-16.6	Denton *et al.* 1999., 2006c
Bohadschia argus (H)	Small boat marinas, Guam	all <0.14	<0.10-0.20[d]	0.18-0.28	6.27-12.6	2.25-3.47	6-96	0.39-0.90	all <0.37	40.6-96.8	Denton *et al.* 1999., 2006c
Bohadschia mormorata (M)	Tanapag Lagoon, Saipan	all <0.12	1.03-10.1	<0.3-0.74	<0.30-0.71	0.45-2.01	0.54-3.04	0.65-1.11	<0.12-0.88	9.92-41.5	This Study
Bohadschia mormorata (H)	Tanapag Lagoon, Saipan	all <0.09	0.60-12.1	<0.11-3.72	3.14-29.7	2.34-5.63	39.0-321	0.47-3.39	<0.30-10.3	93.4-503	This Study
Holothuria atra (M)	Tanapag Lagoon, Saipan	all <0.13	0.61-15.4	all <0.13	<0.28-0.69	0.96-3.10	<0.48-4.55	<0.12-0.45	<0.15-2.09	13.1-24.1	This Study
Holothuria atra (H)	Tanapag Lagoon, Saipan	<0.07-0.25	0.12-2.04	<0.08-0.25	<0.26-4.99	3.11-11.2	5.53-63.2	<0.12-0.77	<0.11-6.33	29.8-287	This Study
Holothuria atra (M)	Pago Bay, Guam	all <0.14	1.77-5.83	all <0.14	<0.09-0.30	0.89-1.62	1.13-4.48	<0.09-0.27	all <0.28	12.8-17.8	Denton *et al.*, 2006b
Holothuria atra (H)	Pago Bay, Guam	all <0.78	1.29-11.2	all <0.78	0.67-13.6	3.75-6.37	3.16-52.3	<0.49-1.16	all <1.57	56.9-301	Denton *et al.*, 2006b
Holothuria atra (M)	Apra Harbor, Guam	all <0.12	13.6-23.2[d]	<0.1-0.1	<0.1-0.3	0.7-1.2	7-8	<0.2	all <0.3	15.5-17.9	Denton *et al.* 1999., 2006c
Holothuria atra (H)	Apra Harbor, Guam	<0.35-4.90	7.24-28.3[d]	0.25-0.26	2.21-8.58	4.70-5.19	49-88	all <0.50	all <0.92	120-180	Denton *et al.* 1999., 2006c
Holothuria atra (M)	Small boat marinas, Guam	<0.01-0.24	all <0.01[d]	<0.1-0.1	all <0.20	1.3-2.5	8-22	all <0.20	all <0.60	12.6-21.2	Denton *et al.* 1999., 2006c
Holothuria atra (H)	Small boat marinas, Guam	<0.11-0.72	<0.01-0.18[d]	0.09-0.12	0.08-3.14	3.69-6.37	16-91	all <0.43	all <0.72	117-253	Denton *et al.* 1999., 2006c
Holothuria sp. (whole)	Townsville coastal waters, Australia	all <0.2	-	<0.2	<0.3-6.3	<0.3-3.5	-	all <0.5	<0.4-3.8	13.9-39.4	Denton, unpublished data
Molpadia intermedia (M)	Georgia Strait, Vancouver (dump site)	-	-	1.7	2.2	26	-	1.7	1.4	171	Thompson & Paton, 1978
Stichopus variagatus (M)	Gt. Barrier Reef, Australia	-	-	all <0.1	-	1.5-2.1	<1-3	all <0.5	all <0.90	1.9-13.9	Burdon-Jones & Denton, 1984
BIVALVES (whole flesh):											
Asaphia violascens	Tanapag Lagoon, Saipan	0.99-1.32	-	0.62-0.70	11.9-12.2	26.5-73.3	-	5.07-7.35	68.1-102	220-332	This Study
Asaphia violascens	Pago Bay, Guam	0.11	-	0.11	0.16	7.61	-	5.87	0.81	72.9	Denton *et al.*, 2006b
Atactodea striata	Tanapag Lagoon, Saipan	<0.23-5.08	1.41-2.19[e]	<0.08-5.45	0.42-1.16	7.35-20.2	8.22-23.8	1.81-4.76	<0.39-3.14	71.8-147	This Study
Atactodea striata	Magnetic Island, N. Queensland, Australia	0.8	-	1.1	1.8	13	-	2.4	2.0	138	Burdon-Jones *et al.* 1975
Ctena bella	Tanapag Lagoon, Saipan	0.33-0.81	0.92	1.16-2.71	0.82-0.92	5.31-14.1	22.0	4.40-5.57	5.94-6.38	384-430	This Study
Ctena bella	Pago Bay, Guam	0.09-0.12	4.59-6.89	0.11-2.51	0.14-0.18	5.79-20.9	5.63-17.4	7.83-21.2	<0.20-1.35	112-289	Denton *et al.*, 2006b
Gafrarium pectinatum	Tanapag Lagoon, Saipan	<0.14-0.62	2.64-4.42	0.78-1.79	0.58-1.31	6.69-35.3	9.91-23.3	10.6-14.1	7.97-46.9	42.3-62.6	This Study
Gafrarium pectinatum	Pago Bay, Guam	0.14	-	1.14	0.21	17	-	16.4	0.27	59.6	Denton *et al.*, 2006b
Gafrarium tumidum	Townsville coastal waters, Australia	5.3-5.7	-	0.3-0.3	0.6-1.6	7.1-7.7	-	64.5-145	3.1-5.1	26.3-68.8	Burdon-Jones *et al.*, 1975
Quidnipagus palatum	Tanapag Lagoon, Saipan	0.32-24.1	1.67-3.24	0.16-1.40	4.46-10.6	14.7-1876	33.6-111	7.30-13.1	9.01-184	305-1027	This Study
Quidnipagus palatum	Pago Bay, Guam	<0.08-0.13	9.71-27.2	<0.08-0.10	<0.13-0.46	4.26-68.5	21.9-62.4	10.4-24.7	0.20-0.89	93.6-341	Denton *et al.*, 2006b
FISH (axial muscle)											
4 spp.	Tanapag Lagoon, Saipan	-	0.29-37.9	-	-	-	3.11-97.4	-	-	-	This Study
50 spp.	Great Barrier Reef, Australia	-	-	all <0.1	-	0.47-2.4	<2-1900	all <0.5	all <0.7	4.3-41.8	Denton & Burdon-Jones 1986b
17 spp.	Apra Harbor, Guam	<0.1-0.2	0.63-24.2[d]	all <0.1	all <0.5	0.5-7.8	12-660	all <0.4	all <0.8	8.3-34.2	Denton *et al.* 1999., 2006c
24 spp.	Small boat marinas, Guam	<0.1-0.3	1.37-77.6[d]	all <0.1	<0.1-0.6	0.3-0.9	9-214	<0.2-<0.7	all <0.9	8.4-48.9	Denton *et al.* 1999., 2006c

[a] Arsenic concentrations as µg/g wet weight; [b] mercury concentrations as ng/g wet weight; [c] (M) = body wall, (H)= hemal system; [d] arsenic concentrations as µg/g dry weight; dashes indicate no data

Plate 5: Bioindicators: Seacucumber, *Holothuria atra* (edible) and brown seaweed, *Padina boryana*

Plate 6: Bioindicators: Seagrass, *Enhalus acoroides*, and (inset) three common resident (edible) bivalves: (a) *Ctenna bella*, (b) *Gafrarium pectinatum* and (c) *Quidnipagus palatum*.

Plate 7: Bioindicator: *Atactodea striata*, (inset) edible bivalve and resident of clean sandy beaches

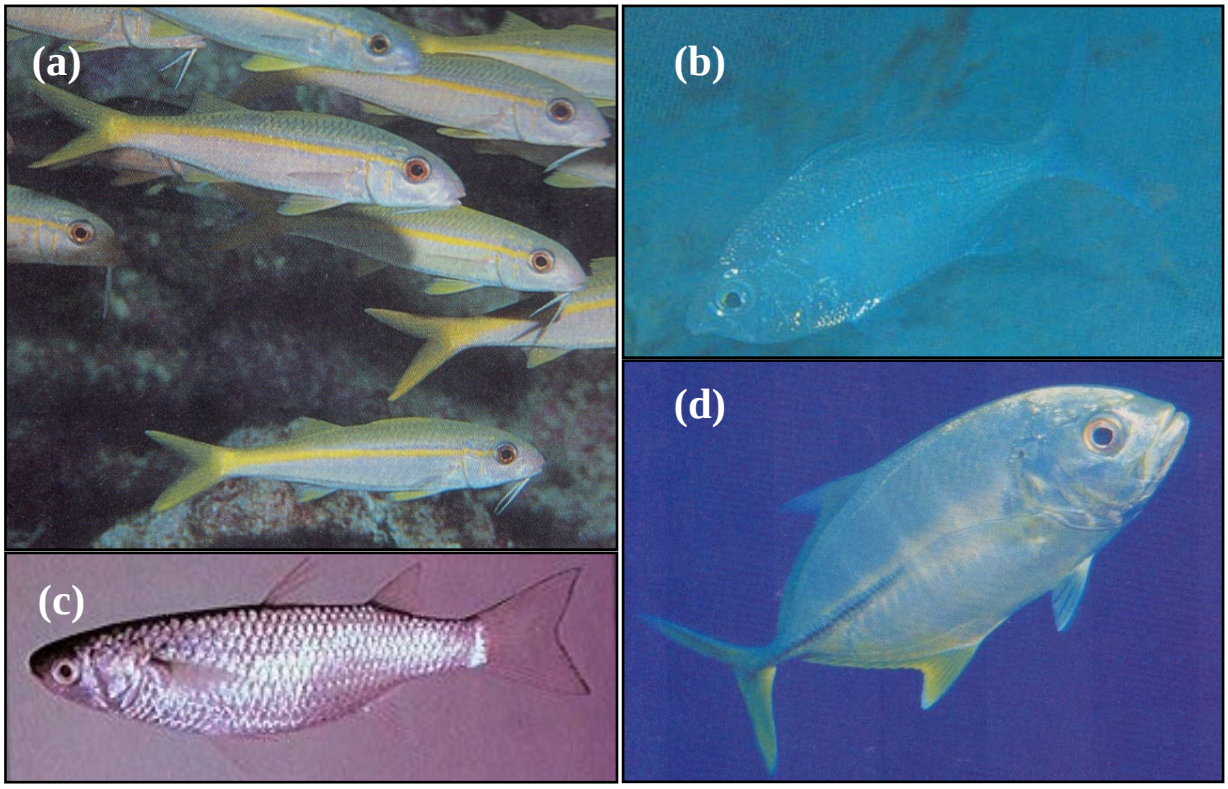

Plate 7: Bioindicators and popular food fish: (a): *Mulloides vanicolensis* (b) *Gerres argyreus*, (c) *Valamugil engeli* and (d) *Carnx sexfasciatus*

RESULTS AND DISCUSSION

The data for all metals considered during this study are summarized in Table 6 for surface sediments and Tables 7-11 for the biota. The tables are located at the end of this section. The findings of the survey are briefly evaluated here with reference to levels found in sediments and similar or related biota from clean and polluted environments from elsewhere. For convenience, these discussions are organized on a metal-by-metal basis and are presented in alphabetical order of each element's chemical symbol identity. All referenced data are expressed on a dry weight basis, unless stated otherwise.

SILVER (Ag):

Silver ranks among the most toxic of heavy metals to marine organisms (Moore 1991). Levels in abiotic components of the marine environment are usually low. Dissolved levels in seawater, for example, are generally less than 0.001 µg/l (Shafer 1995) while levels in uncontaminated sediments are in the order of 0.1 µg/g (Bryan and Langston 1992). Sedimentary silver concentrations in highly polluted environments can exceed 100 µg/g (Skei *et al.* 1972).

Data for Saipan is limited to the southern half of Tanapag Lagoon where measured sedimentary silver concentrations rarely exceeded 0.3 µg/g and were mostly below 0.1 µg/g (Denton *et al.* 2001). The intertidal sediments analyzed during the present study show similarly low silver concentrations with the exception of the sample taken close to the dump (Table 6). An earlier investigation conducted by DEQ in collaboration with the USEPA determined silver in six sediment samples from around the southwest perimeter of this facility and found a high of 2.3 µg/g (DEQ 1987). Interestingly, levels were below analytical detection limits in the remaining five samples which suggest that silver has a rather patchy distribution of enrichment in the area. The findings of the present study lend weight to this hypothesis and also to an earlier claim that silver is generally not an element of environmental concern in the lagoon (Denton *et al.* 2001).

Marine algae and macrophytes generally do not concentrate silver to levels above 0.4 µg/g in clean waters (Preston *et al.* 1972, Bryan and Uysal 1978, Burdon-Jones *et al.* 1975, Denton *et al.* (1980). In metal enriched environments, however, levels may be substantially higher. For example, Bryan and Hummerstone (1977) reported a maximum value of 2.42 µg/g for *Fucus* spp. (brown algae) collected from the metal enriched Looe River estuary in Cornwall, UK. In the current study, silver concentrations rarely exceeded 0.4 µg/g in the algae and seagrass examined (Tables 7-8).

Silver levels in almost all species of echinoderms examined by others are either non-detectable, or near the limits of analytical detection (Eisler 1981). The results of the present study are in line with these findings (Table 9). In a previous investigation, a relatively high silver concentration of 4.9 µg/g was found in hemal tissue of a single specimen of *Holothuria atra* from Apra Harbor in Guam implying that seacucumbers may have indicator capability for this particular element (Denton *et al.* 1999). However, the fact that silver was not detected in the hemal tissue of specimens collected near the dump (site 2) during the current study suggests otherwise.

Mollusks show considerable inter- and intra-specific variations in silver concentrations with levels reported in the literature ranging from <0.1-185 µg/g. In most cases, the highest values

are found in bivalves taken from polluted environments (Eisler 1981). Silver concentrations in specimens examined during the present work (Table 10), while generally low, were appreciably higher than those found in similar species from Pago Bay, a relatively clean coastal site in Guam (Denton *et al.* 2006b, see Table 5). *Quidnipagus palatum* appears to be especially sensitive to changes in the ambient biological availability of this element and clearly reflected the mild silver enrichment noted in sediment from site 2. Tissue concentrations of silver in specimens from this site were approximately two orders of magnitude higher than those found in *Q. palutum* from Guam. Moreover, the substantial difference in silver concentrations noted between the two subpopulations of *Q. palatum* collected from site 2 certainly supports the contention that silver is heterogeneously distributed in sediments in this area.

ARSENIC (As):

Although arsenic has several oxidation states, the chemical form normally encountered in the environment is not particularly toxic to aquatic organisms (Moore 1991). Soluble arsenic levels in seawater are normally around 2-4 µg/l (Riley and Chester 1971, Bowen 1979) while levels in uncontaminated sediments typically range between 1 and 5 µg/g (Bryan and Langston 1992). In highly contaminated environments levels and can exceed 1000 µg/g (Langston 1984, 1985).

Arsenic levels previously determined in sediments around the dump by DEQ (1987), ranged from 2.4-8.6 µg/g with an overall geometric mean of 3.93 µg/g. This was reasonably close to the arsenic concentration of 2.56 µg/g determined in the sediment sample collected from site 2 during the present investigation. Elsewhere in the study area, levels ranged from 0.33-7.78 µg/g with the higher levels generally occurring in the muddier deposits. Clearly, the levels encountered are of no immediate concern from an environmental standpoint.

Appreciable and often highly variable amounts of arsenic are found in most marine organisms. Levels in algae, for example, are typically around 20 µg/g (Bryan 1976) with normal ranges between 2-60 µg/g (Eisler 1981). All specimens analyzed from Tanapag Lagoon during the present study yielded values well within this range with the exception of *Sargassum* which was well over 100 µg/g when expressed on a dry weight basis (Table 7). This particular genera has a relatively high affinity for arsenic as previously demonstrated by Denton *et al.* (2006b). Interestingly, arsenic concentrations in seagrass were considerably lower than those found in algae and rarely exceeded 0.5 µg/g (Table 9). Levels recorded in seagrass from Pago Bay in Guam were similarly low. No other comparable data for arsenic was found in the literature for this group.

Arsenic levels in the seacucumbers examined were generally low (Table 9) and in line those previously recorded for similar species on Guam (Table 5). Bryan (1976) reports an average arsenic value of 5 µg/g for echinoderms generally, but draws attention to the fact that his estimate is derived from very few data. Seacucumbers analyzed here exceeded this value on several occasions when levels recorded were expressed on a dry weight basis. There is some evidence to suggest seacucumbers have bioindicator potential for arsenic (Denton *et al.* 1999) although this remains to be substantiated. Certainly, the highest levels recorded in *Holothuria atra* from Guam came from specimens in Apra Harbor and were attributed to arsenic containing biocides used for anti-fouling purposes.

Bivalves from uncontaminated sites usually contain arsenic concentrations between 1-15 µg/g (Eisler 1981) and specimens analyzed during the present study were mostly within this range. The utility of bivalves as indicators of arsenic pollution has yet to be unequivocally established and the data available for species from this part of the world is not encouraging. For example Denton *et al.* (1999) noted that arsenic levels in oysters were lower in specimens from Apra Harbor in Guam compared with cleaner sites on the island. Likewise, levels found in *Quidnipagus palatum* and *Ctena bella* during the present study were considerably lower than those previously reported for the same species from the cleaner waters of Pago Bay in Guam (Denton *et al.* 2006b).

Arsenic concentrations in edible fish tissues are generally lower than those reported for edible portions of algae, crustaceans, and bivalve mollusks (Lunde 1977). Eisler (1971) conducted an extensive review of arsenic in fish tissue and concluded that while levels in axial muscle tissue varied widely, most fell between 2.0 and 5.0 µg/g wet weight. The results of our study generally confirm these sentiments (Table 11). There is some evidence in the literature to suggest that fish may be useful indicators of arsenic availability. For example, Grimanis *et al.* (1978) found maximum levels of 18.0 and 142 µg/g in the flesh of *Gobius niger* from non-polluted and polluted areas of the Aegean Sea respectively. Likewise, Papadopoulu *et al.* (1973) recorded average concentrations of 18.0 and 39.0 µg/g in the flesh of *Pagellus erythrinus* from clean and contaminated areas of the Mediterranean.

CADMIUM (Cd):

Cadmium, particularly as the free cadmium ion, is highly toxic to most plant and animal species. Fortunately, soluble levels found in uncontaminated aquatic environments are normally well below 1 µg/l (Moore 1991). Non-polluted sediments typically contain around 0.2 µg/g cadmium or less while levels may exceed 100 µg/g at heavily contaminated sites (Naidu and Morrison 1994).

Denton *et al.* (2001) have shown that while cadmium is generally not a problem metal in Tanapag Lagoon, some significant enrichment of sediments does exist around the Puerto Rico Dump. These authors reported cadmium levels of 0.54-0.61 µg/g in samples taken seaward of the current study site. In the earlier investigation carried out by DEQ (1987), sedimentary cadmium levels of 1.0-2.7 µg/g were reported for this area. The cadmium concentration of 1.69 µg/g determined in sediment from site 2 during the present study certainly falls within this range (Table 7) and qualifies as heavily contaminated according to the classification scheme put forward earlier by Denton *et al.* (1997) for reef sediments.

The ability of algae to accumulate cadmium from seawater is well documented and levels as high as 220 µg/g have been recorded in brown algae (*Fucus vesiculosus*) from the metal enriched Severn Estuary in the UK (Butterworth *et al* 1972). Levels recorded during the present study ranged from <0.1-1.72 µg/g. These values compare well with levels found in related species from the Australian Great Barrier Reef (Denton and Burdon-Jones 1986a).

While algae are generally considered to be useful biological indicators of dissolved cadmium, the presence of elevated levels of iron and/or manganese in the water can significantly reduce cadmium uptake (Moore 1991). This is thought to occur as a result of competition between the

metals for cellular binding sites. Since harbors are typically enriched with both metals, some caution is required in interpreting cadmium contamination profiles in such areas from the analysis of algae alone. This phenomenon possibly explains the relatively low cadmium levels noted in algae from the more heavily industrialized southern section of Tanapag during the present study. Whether seagrasses are similarly affected is currently unknown.

Echinoderms generally are not noted for their ability to accumulate cadmium and levels reported in the literature for this group rarely exceed 1.0 µg/g. It seems likely that seacucumbers possess some bioindicator potential for this element in their hemal tissue although the evidence is far from conclusive (Table 9). Nevertheless, the highest levels encountered in this tissue during the present study were found in specimens collected from areas where higher levels of available cadmium are expected to exist, e.g., CUC beach, seaplane ramps and the dump (see Table 9).

Bivalve mollusks have been widely used to monitor cadmium pollution in aquatic environments. The fact that they are sessile and have a high affinity for cadmium, and several other metals of environmental concern, make them ideal candidates for coastal monitoring purposes. However, this latter quality also places severe constraints on their usefulness as a food resource when harvested from heavy metal contaminated waters.

While there is considerable data for cadmium and other heavy metals in bivalves from temperate waters, not much in the way of comparable data exists for the species analyzed during the present investigation. What little data there is has been incorporated into Table 5 and largely reflects previous work conducted on Guam (Denton *et al.* 2006b). Suffice to say, cadmium levels in *Quidnipagus palatum* and the single specimen of *Asaphia violascens* from Saipan were marginally higher than those determined in their counterparts from Guam, whereas levels in *Ctena bella* and *Gafrarium pectinatum* were essentially the same. There was, therefore, no compelling evidence to suggest a significant net increase in the movement of cadmium into biotic food webs had yet occurred around the Saipan dump despite the significant enrichment noted in the sediment from this location.

CHROMIUM (Cr):

Chromium is only moderately toxic to aquatic organisms (Moore 1991). Total dissolved chromium levels in seawater show little variability and range from around 0.6 µg/l in offshore areas to 1-2 µg/l in highly polluted areas (Riley and Chester 1971, Beukema *et al.* 1986). Nakayama *et al.* (1981) showed that dissolve chromium in the Pacific Ocean and Sea of Japan existed as 10-20% inorganic-Cr^{3+}, 25-40% inorganic-Cr^{6+}, and 45-65% organic-Cr. Levels in particulate form were also found to outweigh dissolved concentrations by a factor of 6 and 5.25 in each location respectively. From this we infer that sedimentary chromium levels rapidly accumulate in waters receiving elevated concentrations of this metal.

Chromium levels in uncontaminated sediments vary according to their mineralogical characteristics and range between 10-100 µg/g (Turekian and Wedepole 1961). Calcareous sediments of biogenic origin, like those found on Saipan and Guam, are typically lower and normally contain 3-5 µg/g. In severely contaminated areas, sedimentary chromium concentrations have exceeded 2000 µg/g (Young and Means 1987). Chromium levels determined in intertidal sediment during the current work were all less than 5 µg/g except for the

sample taken from site 2, near the dump, where a high of 17.5 µg/g was recorded. The earlier DEQ investigation found levels of 6.3-39.3 in sediments from this area (DEQ 1987). Thus light to moderate chromium contamination exists here if we adopt the classification scheme put forward by Denton *et al.* (1997) for biogenic carbonates.

Chromium levels in algae and seagrass from clean waters usually range between 1-3 µg/g although lower values have been reported (Table 5). Levels found in specimens from Tanapag Lagoon are in agreement with this (Tables 7-8). In contaminated environments, concentrations may be an order of magnitude higher or more. For example, Burdon-Jones *et al.* (1975, 1982) reported a high of 31.5 µg/g in *Padina* sp. from the upper reaches of Townsville Harbor in north Queensland, Australia, while Gryzhanková *et al.* (1973) recorded a high of 140 µg/g in algae from polluted coastal waters in Japan.

Chromium is clearly compartmentalized in seacumbers with higher levels occurring in the hemal tissue compared with the body wall musculature. These organisms may have some bioindicator capacity for chromium as implied by the work of Thompson and Patton (1978), who found 2.2 µg/g in the body wall of *Molpadia intermedia* from a contaminated sediment disposal site in Georgia Strait, Vancouver, Canada. Levels determined in this tissue during the present study were all less than 1.0 µg/g (Table 9) with the great majority below 0.5 µg/g (Table 9). Hemal tissue chromium concentrations were generally less than 5 µg/g, although a high of 29.7 µg/g was noted in the single specimen of *Bohadschia mormorata* collected from CUC beach (site 5).

Chromium concentrations in the edible tissues of uncontaminated marine mollusks usually lie between 0.5-3.0 µg/g (Eisler 1981). Levels recorded here ranged from less than 1.00 µg/g in *Ctenna bella* from site 1 to over 10.0 µg/g in *Asaphia violascens* and *Quidnipagus palatum* from site 2 (Table 10). All three species were significantly higher in chromium than their counterparts taken from Pago Bay, a clean coastal environment in Guam (Table 5). This clearly demonstrates their sensitivity to changes in ambient concentrations of this element and provides additional evidence of light chromium enrichment around the dump in Tanapag Lagoon..

COPPER (Cu):

Copper is particularly noxious to plants and invertebrates (Brown and Ahsanulla 1971, Denton and Burdon-Jones 1982), and ranks among the more toxic heavy metals to fish (Denton and Burdon-Jones 1986b, Moore 1991). Dissolved copper levels in open ocean surface waters are low, being generally in the order of 0.2 µg/l, or less. In uncontaminated nearshore surface waters, levels are significantly higher, often approaching 1 µg/l, while in highly polluted waters they may exceed 10 µg/l (Burdon-Jones and Denton 1984).

Copper levels in clean, non-geochemically enriched coastal sediments rarely exceed 10 µg/g whereas values in excess of 2,000 µg/g can occur in severely polluted environments (Legoburu and Canton 1991, Bryan and Langston 1992). Clean coral reef sediments typically contain 1-3 µg/g copper nearshore, whereas levels of 0.1 µg/g, or less, are frequently encountered further offshore away from terrestrial influences and contributing anthropogenic sources (Denton *et al.* 2001).

In the current study, sedimentary copper levels ranged from a low of 0.5 µg/g in the clean, course sand from Micro Beach (site 1) to a high of 102 µg/g in the muddy deposits close to the dump (site 2). Previous analysis of sediments from around the dump revealed copper levels of 4.8-68.8 µg/g (DEQ 1987; Denton *et al.* 2001). The degree of copper contamination in this area therefore ranges between light and grossly polluted according to the classification scheme put forward by Denton *et al.* (1997) for bioclastic deposits. The copper level determined here in sediment from Seaplane Ramps (site 4) was also relatively high (39.8 µg/g) and places this site in the moderately polluted category.

Copper concentrations recorded in seaweeds and seagrass during the present investigation were almost always less than 10 µg/g. The notable exceptions in both groups were at Seaplane Ramps were levels ranged from 25-30 µg/g in algae and approached 50 µg/g in the single sample of seagrass analyzed (Tables 6-7). Marine plants normally contain copper levels of less than 10 µg/g, except near polluting sources where values in excess of 50 µg/g are not uncommon (Moore 1991). They also tend to mirror changes in the dissolved metal fraction of the water column rather than that associated with sediments and suspended particulate material (Phillips 1980). Thus, copper based antifouling paints were considered to be the most likely source of elevated soluble copper at Seaplane Ramps in view of the ongoing dry dock activities in this area and the relatively modest copper levels present in the sediments there. The opposite scenario exists near the dump where dissolved copper levels are obviously low despite significant enrichment in the sediments. Clearly, copper contamination at this site originates from sources that do not significantly influence concentrations of this element in the overlying water column.

Seacucumbers concentrate copper more so in hemal tissue than body wall muscle and there are indications from the present study that the latter tissue has bioindicator capability for this element. In *Bohadschia mormorata*, for example, hemal copper levels were notably higher at Seaplane Ramps compared from specimens collected from the other three sites (Table 9). *Holothuria atra* from the dump and Seaplane Ramps were similarly enriched compared with specimens collected elsewhere in the study area. There is no evidence here to indicate that the body wall of seacucumbers has the same capability.

Bivalve mollusks have been used extensively to monitor copper in the marine environment, although some species are far more sensitive to ambient changes in the biological availability of this element than others. Not much is known about the bioindicator potential of the species examined here although what little information there is suggests *Quidnipagus palatum* is an extremely promising candidate. Specimens from a clean section of Pago Bay in Guam, for example, yielded a maximum copper concentration 4.8 µg/g compared with an impressive 1,876 µg/g in specimens collected near the dump during the present study (Table 10). A similar data-set comparison for *Gafrarium pectinatum* also highlights the copper enrichment around the Saipan dump but not with the same degree of sensitivity as that demonstrated by *Q. palatum*. Nevertheless, both species indicate a progressive increase in ambient copper availability as one moves south from Lower Base Channel (site 6) to the Puerto Rico Dump (site 2).

MERCURY (Hg):

Mercury is highly toxic to aquatic organisms, particularly in the organic form (Moore 1991). Concentrations of dissolved mercury in the open ocean typically range from <0.001-0.003 µg/l

(Miyake and Suzuki 1983) whereas values of 0.003-0.20 µg/l are typically found closer to shore and polluted estuarine waters may contain up to 0.060 µg/l (Baker 1977).

Sediment concentrations of mercury in unpolluted, non-geochemically enriched areas usually do not exceed 30 ng/g (Bryan and Langston 1992, Benoit *et al.* 1994) and may be as low as 2 ng/g in clean bioclastic sediments (Denton *et al.* 1997, 2001). Estuarine sediments, adjacent to heavy industrialized areas or mercury mining activities, can be three to five orders of magnitude higher than this (Langston 1985, Benoit *et al.* 1994). Values in excess of 2000 µg/g were found in sediments from the grossly contaminated Minimata Bay area in Japan, following the mass mercury-poisoning episode of the late 1950's, and probably rank among the highest values ever reported for this element (Tokuomi 1969).

Levels found in intertidal sediments from Tanapag Lagoon during the present study ranged from less than 5 ng/g in the clean coarse beach sands to 74.7 ng/g in sediment collected close to the dump (Table 6). Earlier studies have reported mean mercury levels of 151 ng/g (DEQ 1987) and 101 ng/g (Denton *et al.* 2001) in sediments from the latter area (Table 5).

Mercury is the only metal that tends to become more concentrated at higher trophic levels, a process known as biomagnification. Levels in marine algae from clean environments are generally less than 20 ng/g wet weight and may be as low as 1 ng/g or less (Denton and Burdon Jones 1986a). In the present study, mercury values for all species of algae analyzed ranged from 0.45-10.2 ng/g wet weight and rank among the lowest ever recorded. Levels of the same order were found in seagrass and the body wall of seacucumbers while substantially higher values were found in the hemal system of the latter group. In his review of the literature, Eisler (1981) concluded that mercury levels in echinoderms from non-polluted environments never exceed 400 ng/g wet weight, which is slightly above the highest level encountered here. A more appropriate upper benchmark for the seacucumbers examined here is 5 and 50 ng/g wet weight in the body wall and hemal system respectively. In an earlier study, it was concluded that mercury levels in Guam seacumbers generally mirrored those in site sediments (Denton *et al.* 1999). The same appears to hold true here, at least in hemal system.

Although bivalve mollusks are excellent accumulators of mercury, tissue concentrations in specimens from clean environments rarely go beyond 100 ng/g wet weight. During the current investigation, only *Quidnipagus palatum* from the dump site exceeded this value with a high of 111 ng/g wet weight. Levels encountered in bivalves from all other sites ranged from 8.22-62.4 ng/g wet weight, and reinforce an earlier claim that the nearshore waters of Tanapag Lagoon are, for the most part, only lightly contaminated with mercury (Denton *et al.* 2001, 2006a).

Mercury levels in fish are generally higher than found in most invertebrate species and tend to be age and trophic level dependant. Thus, highest natural levels are usually found in the larger, long-lived, predatory species like sharks, tuna, marlin and swordfish (Bligh and Armstrong 1971, Windom *et al*. 1972, Rivers *et al.* 1972, Nishigaki *et al.* 1973, Beckett and Freeman 1974, Mackay *et al.* 1975, Shultz and Crear 1976, Denton and Breck 1981). In some cases, levels of mercury in fish from remote areas have been known to exceed maximum values recommended for human consumption (Denton and Burdon Jones 1986c).

In non-polluted situations, mercury levels in fish are generally less than 200 ng/g wet weight (Holden 1973, Denton and Burdon-Jones 1986c). Since fish possess little ability to regulate tissue levels of mercury in the same way as they do essential elements like copper and zinc, they serve as useful biological indicators for this metal. Fish flesh analyzed from Minimata Bay, for example, contained up to 309,100 ng/g wet weight, way beyond levels considered safe for human consumption. It should be noted here that mercury has caused more problems to consumers of fish than any other inorganic compound (Irukayama *et al.* 1961).

In the present study, several hundred juvenile fish representing four different species were pooled in small groups for analysis. While all samples contained detectable quantities of mercury, none yielded concentration in excess of 100 ng/g wet weight. Moreover, similar ranges were found within each species with minimum values varying from 3.11-17.9 ng/g wet weight and maximum values from 42.7-97.4 ng/g wet weight (Table 11). Clearly, mercury levels in the four species of juvenile fish analyzed here do not present a significant health hazard to people who catch and consume them.

NICKEL (Ni):

Nickel is only moderately toxic to most species of aquatic plants and is one of the least toxic heavy metals to invertebrates and fish (Denton and Burdon-Jones 1982, 1986b, Moore 1991). Open ocean concentrations of dissolved nickel normally lie between 0.1 and 0.3 µg/l (Boyle *et al.* 1981, Bruland 1980, Denton and Burdon-Jones 1986d). In polluted nearshore and estuarine waters, levels of between 5 and 30 µg/l have been reported (Halcrow *et al.* 1973, Abdulla and Royle 1974, Boyden 1975).

Total nickel residues in lithogenic sediments normally range between 10-20 µg/g (Bryan and Langston 1992) but can exceed 200 µg/g (Fowler *et al.*1993) in contaminated regions. Clean bioclastic sediments from Guam and Saipan coastal waters typically contain concentrations of less than 1 µg/g (Denton *et al.* 1997, 2001). The highest nickel levels previously found near the dump in Tanapag Lagoon range from 5.23 µg/g (Denton *et al.* 2001) to 16.1 µg/g (DEQ 1987). Sediment collected from this location (site 2) during the present study contained 11.9 µg/g, well within the earlier data range. Elsewhere in the study area, levels rarely exceeded 1 µg/g and clearl indicate that nickel is not a problem element in these waters.

Brown algae rarely concentrate nickel above 3 µg/g in uncontaminated environments (Denton and Burdon Jones 1986a), whereas levels in excess of 30 µg/g have been recorded in specimens from nickel-enriched waters (Stevenson and Ufret 1966). Levels recorded in all algae and seagrass samples during the present work were all less than 3 µg/g.

Seacucumbers do not appear to be particularly sensitive indicators of nickel pollution (Denton *et al.* 1999), although one study reported whole body levels of 38 µg/g in *Stichopus tremulus* from an unspecified location (Noddack and Noddack 1939). All other studies suggest that levels in the body wall and hemal tissue do not deviate much beyond 1-2 µg/g regardless of ambient nickel concentrations (Table 5). Levels determined in both tissues during the current study rarely exceeded 3 µg/g and were almost always less than 1 µg/g (Table 9).

Bivalves are generally more affective accumulators of nickel than seacucumbers, although their bioindicator capacity for this element also remains in question. Certainly the similarities between Tanapag Lagoon and Guam data sets for *Gafrarium pectinatum* and *Quidnipagus palatum* (Table 5) suggest both species exert some metabolic control over this element, considering that sediments near the Puerto Rico Dump are lightly nickel enriched.

LEAD (Pb):

Although inorganic lead is only moderately toxic to aquatic plants and animals, organolead compounds, particularly those used as antiknock agents in gasoline, are highly toxic to all forms of life (Moore 1991). Inorganic lead is barely soluble in seawater and levels in open ocean waters typically range from 0.005-0.015 µg/l. Even in highly polluted waters, levels are unlikely to rise much above 0.050 µg/l (Burnett *et al*. 1977). Thus, particulate lead accounts for >75% of total lead in most waters (Moore 1991).

Lead concentrations in clean, non-geochemically enriched, lithogenic sediments generally do not exceed 25 µg/g (Bryan and Langston 1992), while levels in clean bioclastic deposits rarely exceed 1.0 µg/g (Denton *et al.* 2001, 2006a,b). In severely polluted locations, near mining activities, or industrial processes that utilize lead, sedimentary lead concentrations may exceed 2,000 µg/g (Jones 1986, Bryan and Langston 1992). The highest level reported to date is 266,000 µg/g in sediments adjacent to a battery factory in Suva Harbor, Fiji (Naidu and Morrison 1994).

Lead levels recorded in intertidal sediments during the present investigation ranged from a low of 0.65 µg/g in the clean coarse sands of Micro Beach (site 1) to a high of 158 µg/g in the gravelly mud at the base of the dump (site 2). Levels previously determined by DEQ from the latter location, over twenty years ago, ranged from 5.8-201 µg/g (DEQ 1987). More recently, Denton *et al.* (2001, 2006a) detected levels of 9.5-43.4 µg/g. Such variability in these data clearly demonstrates a highly heterogeneous distribution of sediment associated lead in the area. The relatively high level found at site 2 during the current study falls within the grossly contaminated category of the classification scheme devised by Denton *et al.* (1997) for bioclastic deposits. By the same principle, intertidal sediments from Seaplane Ramps (site 4) and CUC beach (site 5) may be described as moderately contaminated with lead while deposits from elsewhere in the study area are relatively clean by world standards (Table 6).

While algae generally have a high affinity for lead and may concentrate it to well over 100 µg/g in polluted waters, levels in specimens from clean environments rarely exceed 1 µg/g (Denton and Burdon-Jones 1986a). In the present study, lead concentrations ranged from <0.23-14.7 µg/g with the highest levels occurring in specimens from site 4 at Seaplane Ramps (Table 7). This is interesting considering the much higher sedimentary lead levels found at site 2 near the dump. Nevertheless, the algal and seagrass data indicate that dissolved lead concentrations in the water column are higher at Seaplane Ramps than the dump and presumably reflect greater contributions from boat fuels, antifouling and anticorrosive paints at the latter location.

From the literature, it would seem that echinoderms are unable to regulate lead levels in their tissues and, therefore, may serve as potentially useful indicators of environmental contamination by this metal. For example, Stenner and Nickless (1974) reported lead levels of up to 460 µg/g

in various echinoderms from the West Coast of Norway. Matsumoto (1964) gave values of up to 14.4 µg/g wet weight in *Holothuria* sp. from lead-contaminated coastal waters of Japan, while Denton (unpublished data) found 3.8 µg/g in the same genera from a residential beach in Townsville, Australia. In contrast, specimens of *Stichopus variagatus*, from pristine waters of the Great Barrier Reef, contained <1.0 µg/g of lead in their body wall muscle (Burdon-Jones and Denton 1984).

Lead levels found in seacucumbers during the present work, while low by world standards, generally reflected the enrichment noted at the dump and Seaplane Ramps sites in both tissues examined, although concentrations were generally higher in the hemal tissue compared with the body wall (Table 9). The data certainly supports the idea that these organisms have bioindicator potential for this element and the fact that they are so abundant and widespread makes them attractive candidates for such purposes. However their affinity for this element pales in comparison to that demonstrated by the bivalves *Quidnipagus palatum, Asaphia violescens* and *Gafrarium pectinatum*. These three species are particularly sensitive to changes in ambient lead concentrations and between them clearly demonstrate significant enrichment at sites 2, 3 and 5 (Table 10). The highest levels encountered in each species were 184, 102 and 54.2 µg/g respectively. Baseline levels for all three are normally less than 1 µg/g (Denton *et al.* 2006b).

ZINC (Zn):

Although zinc is not appreciably toxic, it is a ubiquitous contaminant and is sometimes released into the aquatic environment in substantial quantities (Bryan and Langston 1992). Surface water concentrations in the open ocean hover around 0.01 µg/l (Bruland *et al.* 1978, Bruland 1980) while closer to shore they are generally higher and show greater variability. A mean value of 0.161 µg/l was reported by Bruland and Frank (1981) for uncontaminated coastal waters of the NW Atlantic, and Denton and Burdon-Jones (1986d) recorded levels of 0.06-0.44 µg/l in waters from the Australian Great Barrier Reef. In harbor environments and polluted estuaries, dissolved zinc levels are considerably higher, and typically range from 10-50 µg/l (Preston *et al.* 1972, Abdullah and Royle 1974, Zingde *et al.* 1976, Burdon-Jones *et al.* 1982, Scoullos and Dassenakis 1983). One of the highest levels recorded is 305 µg/l from Restronguet Creek, a tidal arm of a large Cornish estuary in the UK that drains an area of heavily mineralized Devonian rocks and ancient mine workings (Klumpp and Peterson 1979).

Lithogenic sediments from uncontaminated waters typically contain zinc levels of 5-50 µg/g depending upon local geology (Moore 1991). Residues exceeding 3,000 µg/g are frequently found in the vicinity of mines and smelters (Bryan *et al.* 1985) and in contaminated harbor environments (Poulton 1987, Legorburu and Canton 1991). Levels in nearshore bioclastic deposits are normally within 3-5 µg/g, and may drop below 1 µg/g in clean coral sands (Denton *et al.* 1997, 2001).

Sedimentary zinc levels previously reported by us for nearshore waters in Tanapag Lagoon ranged from 1.63-127 µg/g and peaked at a site off the southwestern edge of the dump (Denton *et al.* 2001). DEQ discovered levels of 15.8-324 µg/g at this same location over a decade beforehand (DEQ 1987). An equally high value of 358 µg/g was found here during the present investigation (Table 6). Significant enrichment above background was also noted in sediments from the Seaplane Ramps (84.0 µg/g) and CUC Beach (26.4 µg/g) sites. Levels exceeding 100

µg/g in bioclastic sediments fall into the heavily contaminated category (Denton *et al.* 1997), whereas values between 10 µg/g and 50 µg/g are representative of light enrichment.

Marine algae are particularly good bioindicators of zinc contamination although levels rarely exceed 10 µg/g in specimens from clean waters (Denton and Burdon-Jones 1986a). In contrast, levels several orders of magnitude higher have been recorded in specimens from severely polluted environments (Bryan and Hummerstone 1973, Fuge and James 1973, Haug *et al.* 1974, Stenner and Nickless 1974, Melhuus *et al.* 1978). Harbor waters and marinas are typically enriched with soluble zinc leached predominantly from boat paints, galvanized structures and sacrificial anodes of water craft. Not surprisingly then, the highest levels encountered in algae during the present study were found at Seaplane Ramps, Echo Bay and Micro Beach at the mouth of Smiling Cove Marina.

A reasonably good trace metal database now exists for *Padina* spp. from countries within the Indo-Pacific region (Table 5). The published information from Australian waters is particularly useful here because it provides zinc data from specimens taken from the pristine waters of the Great Barrier Reef (3.98-9.5µg/g) to the relatively polluted waters of Townsville Harbor (up to 440 µg/g). This tropical member of the phaeophyceae (brown algae) is particularly abundant on Guam and Saipan making it an attractive candidate for any future monitoring program throughout the region. Levels previously recorded for *Padina* sp. from Guam approached 200 µg/g in specimens from Apra Harbor, almost double the highest concentration found in Tanapag Lagoon during the present study (Table 7). The relatively low levels found in specimens from the Puerto Rico Dump site are noteworthy considering the high levels of sedimentary zinc that occur here. Clearly, sources of zinc at this site are very different from those with high boating densities.

Although seagrasses reflect soluble metal contributions from the water column and sediment pore waters, they are considerably less sensitive than algae to changes in ambient zinc availability. Nevertheless, the fact that the highest levels found during the present study came from samples collected close to the dump suggests they do have some, albeit limited, bioindicator potential for this element. The range of zinc concentrations found in specimens from Tanapag Lagoon (20.6-32.7 µg/g) was certainly well above that found in comparable species from the relatively clean waters of Pago Bay (5.25-15.5 µg/g) in Guam (Denton *et al.* 2006b).

In echinoderms, zinc concentrations in excess of 100 µg/g are not unusual. On the strength of this alone, Eisler (1981) proposed that representatives of this group could be used as bioindicators of zinc contaminated waters. However, recent evidence gathered here and suggests otherwise. For example, the range of zinc concentrations found in the body wall of *Holothuria atra* from zinc contaminated sediments in the southern half of Tanapag Lagoon (13.1-24.1 µg/g) was almost identical to that found in specimens from the cleaner sites further north (15.2-22.6 µg/g). Likewise, hemal tissue concentrations of zinc, though higher than those found in body wall, were not significantly different between the two sample groups (Table 9). Moreover, zinc concentrations in both tissues were very similar to those found in clean and contaminated sites on Guam (Denton *et al.* 1999, 2006b,c).

Bivalves are frequently used to monitor zinc levels in the marine environment although little data exists for the species examined during the present study. Based on data-set comparisons with specimens collected from Pago Bay in Guam, *Quidnipagus palatum* obviously possesses some bioindicator potential for zinc, whereas *Gafrarium pectinatum* clearly does not (Denton *et al*. 2006b). Levels recorded in the former species from Tanapag Lagoon ranged from 305-1,027 µg/g (mean: 622 µg/g) compared 93.6-341 µg/g (mean 222 µg/g) in specimens from Pago Bay. *Ctenna bella* also appears to have bioindicator potential for this element with levels approximately 50% lower in specimens from Pago Bay compared with those analyzed during the present study (Table 5).

Table 6: Heavy Metals in Intertidal Sediments from Tanapag Lagoon, Saipan

Site	Location	Sediment Type	Metal (µg/g dry weight)								
			Ag	As	Cd	Cr	Cu	Hg*	Ni	Pb	Zn
1	Micro Beach	Clean coarse sand	<0.20	0.62	<0.20	3.27	0.50	3.70	<0.20	0.65	2.42
2	Puerto Rico Dump	Medium to coarse muddy sand	0.75	2.56	1.69	17.5	102	74.7	11.9	158	358
3	Echo Bay	Medium to coarse sand	<0.21	3.55	0.31	2.56	6.76	18.1	<0.20	3.19	7.39
4	Sea Plane Ramps	Muddy sand	<0.15	5.68	0.23	2.83	39.8	23.0	0.89	17.7	84.0
5	CUC Beach	Muddy sand	<0.16	2.14	0.32	4.61	5.34	24.2	0.94	21.3	26.4
6	Lower Base Channel	Muddy sand	<0.10	2.52	0.24	2.43	1.34	10.9	0.46	1.78	6.00
7	Saddock As Agatan	Fine to coarse muddy sand	<0.17	7.79	<0.17	3.08	4.70	6.90	0.85	0.84	15.1
8	Saddock Dogas	Fine muddy sand	<0.18	2.50	<0.18	3.67	5.79	50.2	1.16	1.33	18.5
9	Bobo Achugao	Fine to medium sand	<0.17	0.28	<0.17	1.42	4.80	3.28	0.25	4.07	12.1
10	Plumaria Hotel Beach	Clean coarse sand	<0.18	1.19	<0.18	2.78	2.53	4.37	0.26	2.19	12.0
11	San Roque Cemetery	Clean coarse sand	<0.15	0.33	0.22	1.71	0.60	2.38	0.22	1.08	3.73
12	Pau Pau Beach	Clean coarse sand	<0.18	0.74	0.27	1.52	2.70	3.31	0.44	1.16	4.49

* mercury concentrations expressed as ng/g dry weight

Table 7: Heavy Metals in Algae from Tanapag Lagoon, Saipan

Sample	Site	Location	Metal (µg/g dry weight)								
			Ag	As[a]	Cd	Cr	Cu	Hg[b]	Ni	Pb	Zn
Acanthophora spicifera	1	Micro Beach	<0.08	0.76	0.23	0.51	5.04	1.86	2.07	0.64	57.4
	4	Sea Plane Ramps	0.51	0.53	0.13	1.29	30.5	4.39	1.87	8.14	130
	7	Saddok As Agatan	0.23	1.13	0.70	1.16	4.41	2.25	1.94	0.97	17.6
	8	Saddok Dogas	0.15	0.77	0.58	0.97	2.88	6.26	1.90	0.49	22.2
	9	Bobo Achugao	0.23	0.93	0.69	1.54	4.17	4.69	2.52	0.96	22.6
	10	Plumaria Hotel Beach	<0.08	0.79	0.62	<0.26	4.40	10.2	1.78	0.65	21.1
Dictyota bartayresiana	11	San Roque Cemetery Beach	<0.16	4.50	0.47	0.56	1.87	3.54	1.28	0.63	29.6
Gracilaria salicornia	2	Puerto Rico Dump	<0.07	2.62	<0.07	<0.23	1.22	4.38	0.22	1.04	11.6
	3	Echo Bay	<0.09	2.40	<0.09	<0.31	2.28	4.26	<0.19	<0.31	17.1
	5	CUC Beach	<0.07	2.19	<0.07	<0.23	1.71	2.43	0.22	<0.23	14.2
	6	Lower Base Channel	<0.11	2.49	<0.11	0.93	2.63	2.42	0.46	<0.37	14.5
	9	Bobo Achugao	<0.10	2.82	0.20	0.83	2.90	2.76	0.52	1.17	24.8
Laurencia sp.	2	Puerto Rico Dump	0.24	0.18	0.78	1.12	4.15	2.91	2.66	3.16	39.4
	3	Echo Bay	0.18	3.24	0.44	1.62	11.3	6.18	2.39	4.27	54.6
Padina sp.	2	Puerto Rico Dump	0.21	7.53	<0.11	0.53	2.80	6.33	0.88	5.47	17.5
	3	Echo Bay	0.29	5.98	0.29	0.84	8.44	3.99	1.05	3.12	60.1
	4	Sea Plane Ramps	0.11	3.56	0.22	1.43	25.3	3.10	1.12	14.7	107
	7	Saddok As Agatan	0.26	4.16	1.72	0.88	2.01	6.02	1.65	1.76	10.6
	8	Saddok Dogas	0.16	7.60	0.97	0.67	1.98	2.65	1.52	<0.27	12.1
	10	Plumaria Hotel Beach	<0.10	5.32	0.58	<0.32	1.30	3.69	1.11	<0.32	5.32
	11	San Roque Cemetery Beach	<0.09	12.25	0.64	0.46	2.02	1.74	1.42	1.06	18.5
	12	Pau Pau Beach	<0.09	7.03	0.63	<0.30	2.02	3.91	1.41	<0.30	7.76
Sargassum polycystum	11	San Roque Cemetery	<0.16	22.94	0.40	0.57	1.27	0.45	1.08	0.51	15.9

[a] Arsenic concentrations as µg/g wet weight; [b] mercury concentrations as ng/g wet weight

Table 8: Heavy Metals in Seagrass from Tanapag Lagoon, Saipan

Species	Site	Location	Statistic[a]	Metal (µg/g dry weight)								
				Ag	As[b]	Cd	Cr	Cu	Hg[c]	Ni	Pb	Zn
Enhalus acaroides	1	Micro Beach	mean	<0.15	0.03	0.15	0.32	7.19	3.38	0.95	0.24	24.1
			range	-	-	-	-	-	-	-	-	-
	2	Puerto Rico Dump	mean	nc	0.07	0.30	0.44	7.77	3.82	2.24	0.69	32.7
			range	all <0.20	-	0.29 - 0.32	0.33 - 0.60	7.66 - 7.88	-	2.14 - 2.34	0.68 -0.71	32.6 - 33.0
	4	Sea Plane Ramps	mean	nc	0.07	0.20	0.44	47.9	3.83	0.76	2.05	29.0
			range	all <0.20	-	-	-	-	-	-	-	-
	5	CUC Beach	mean	nc	0.13	0.54	0.34	6.57	9.01	0.76	0.23	22.8
			range	all <0.20	-	0.48 - 0.60	0.30 - 0.34	5.66 - 7.63	-	0.60 - 0.95	0.22 - 0.24	20.3 - 25.7
	6	Lower Base Channel	mean	<0.17	0.14	0.33	0.87	5.31	0.85	1.85	0.40	25.0
			range	-	-	-	-	-	-	-	-	-
	7	Saddok As Agatan	mean	nc	0.08	0.22	0.33	2.09	1.74	1.42	0.24	21.0
			range	all <0.17	0.03 - 0.24	0.20 - 0.25	0.35 - 0.35	2.03 - 2.15	1.72 -1.77	1.25 - 1.61	0.22 - 0.27	20.1 - 21.9
	8	Saddok Dogas	mean	nc	0.19	0.31	0.56	2.38	1.44	1.03	0.41	22.3
			range	all <0.20	-	0.24 - 0.41	0.35 - 0.87	2.24 - 2.53	-	0.99 - 1.08	0.26 - 0.66	20.8 - 23.8
	9	Bobo Achugao	mean	<0.16	0.09	0.39	0.33	2.64	1.14	1.51	0.25	20.6
			range	-	-	-	-	-	-	-	-	-
Halodule uninervis	5	CUC Beach	mean	nc	0.11	0.66	0.47	6.46	1.8	0.85	0.53	27.6
			range	all <0.20	-	0.64 - 0.66	0.47 - 0.69	6.00 - 6.46	-	0.70 - 0.85	0.52 - 0.53	25.7 - 27.6
	9	Bobo Achugao	mean	<0.20	0.15	0.30	0.42	4.15	2.34	1.25	0.32	35.8
			range	-	0.07	-	-	-	2.35	-	-	-
	10	Plumaria Hotel Beach	mean	nc	0.13	0.47	0.46	4.90	2.67	1.15	1.01	31.6
			range	all <0.20	0.03 - 0.54	0.38 - 0.56	0.41 - 0.50	4.62 - 5.20	2.25 - 3.18	1.09 - 1.21	0.93 - 1.09	30.4 - 32.7
	11	San Roque Cemetery Beach	mean	<0.20	0.12	0.29	0.42	2.45	3.53	1.05	0.32	21.1
			range	-	-	-	-	-	-	-	-	-

[a] Mean as geometric mean; [a] arsenic concentration as µg/g wet weight; [b] mercury concentrations as ng/g wet weight

Table 9: Heavy Metals in Seacumbers from Tanapag Lagoon, Saipan

Species	Site	Location	Tissue[a]	Statistic[b]	Metal (µg/g dry weight)								
					Ag	As[c]	Cd	Cr	Cu	Hg[d]	Ni	Pb	Zn
Bohadschia argus	8	Saddok Dogas	M	mean	<0.09	7.45	<0.09	<0.37	0.86	3.42	0.30	<0.14	15.9
				range	-	-	-	-	-	-	-	-	-
			H	mean	<0.11	0.59	0.32	4.27	2.48	36.3	0.44	<0.36	44.2
				range	-	-	-	-	-	-	-	-	-
B. mormorata	3	Echo Bay	M	mean	nc	1.46	nc	0.34	0.47	2.00	0.76	nc	12.6
				range	all <0.12	1.34 - 1.58	all <0.12	<0.32 - 0.71	0.45 - 0.50	1.31 - 3.04	0.66 - 0.87	all <0.20	12.3 - 12.8
			H	mean	nc	1.53	0.12	4.91	2.76	83.9	0.70	0.91	152
				range	all <0.11	0.73 - 3.20	<0.11 - 0.27	3.68 - 6.54	2.71 - 2.82	59.5 - 118	0.66 - 0.74	0.59 - 1.40	102 - 227
	4	Sea Plane Ramps	M	mean	nc	2.18	nc	nc	1.13	0.82	0.82	0.65	10.7
				range	all <0.08	1.71 - 2.78	all <0.08	all <0.34	0.63 - 2.01	0.54 - 1.25	0.80 - 0.85	0.64 - 0.67	10.2 - 11.3
			H	mean	nc	0.91	0.38	6.71	5.22	79.1	0.80	3.25	161
				range	all <0.13	0.60 - 1.39	0.36 - 0.39	4.83 - 9.31	4.83 - 5.63	76.0 - 82.4	0.68 - 0.94	2.87 - 3.68	118 - 221
	5	CUC Beach	M	mean	<0.08	10.1	<0.08	0.56	1.50	2.89	1.11	0.88	41.5
				range	-	-	-	-	-	-	-	-	-
			H	mean	<0.12	12.1	3.72	29.7	5.23	321	3.39	10.3	503
				range	-	-	-	-	-	-	-	-	-
	6	Lower Base Channel	M	mean	<0.11	1.03	<0.11	0.74	0.53	1.58	0.65	<0.17	9.92
				range	-	-	-	-	-	-	-	-	-
			H	mean	<0.09	1.46	0.36	3.14	2.34	39.0	0.47	<0.30	93.4
				range	-	-	-	-	-	-	-	-	-
Holothuria atra	1	Micro Beach	M	mean	nc	7.30	nc	nc	1.90	2.61	nc	0.19	18.7
				range	all <0.13	5.32-10.3	all <0.13	all <0.56	1.58 - 2.29	1.50 - 4.54	all <0.23	<0.21 - 0.36	18.3 - 19
			H	mean	nc	0.51	0.10	nc	3.13	8.62	nc	0.28	44.5
				range	all <0.12	0.50 - 0.53	<0.08 - 0.25	<0.41	3.11 - 3.16	5.53 - 13.4	all <0.26	<0.41 - 0.39	40.0 - 49.5
	2	Puerto Rico Dump	M	mean	nc	1.38	nc	0.37	1.27	1.83	0.19	1.79	13.8
				range	all <0.09	0.75 - 2.53	all <0.09	<0.41 - 0.66	1.25 - 1.29	1. 65 - 2.02	< 0.16 - 0.45	1.53 - 2.09	13.1 - 14.5
			H	mean	nc	1.56	0.70	2.33	8.18	30.8	nc	4.33	153
				range	all <0.07	1.19 - 2.04	0.56 - 0.86	1.91 - 2.83	7.76 - 8.63	19.8 - 47.9	all <0.14	2.96 - 6.33	95.2 - 246
	3	Echo Bay	M	mean	nc	0.44	nc	nc	1.30	3.39	nc	nc	15.9
				range	all <0.12	0.40 - 0.49	all <0.12	all <0.54	1.30 - 1.77	2.99 - 3.5	all <0.21	all <0.45	13.1 - 19.2
			H	mean	nc	0.49	0.25	0.66	3.91	53.6	nc	0.29	42.8
				range	all <0.12	0.21 - 1.15	0.17 - 0.37	0.49 - 0.89	3.33 - 4.60	45.5 - 63.2	all <0.22	0.20 - 0.41	31.7 - 57.8
	4	Sea Plane Ramps	M	mean	nc	1.51	nc	0.32	1.59	1.83	0.12	1.84	22.7
				range	all <0.08	0.82 - 2.77	all <0.08	<0.33 - 0.62	1.50 - 1.69	1.46 - 2.31	<0.13 - 0.22	1.77 - 1.91	21.4 - 24.1
			H	mean	nc	0.48	0.95	3.39	9.41	12.0	0.34	3.92	276
				range	all <0.11	0.24 - 0.99	0.95 - 1.05	2.94 - 3.90	7.88 - 11.2	8.14 - 17.5	0.25 - 0.46	3.62 - 4.24	266 - 287

[a] Tissues: M = body wall muscle, H = hemal system; [b] mean as geometric mean (n = 1-2 replicates samples per site); [c] arsenic concentrations as µg/g wet weight; [d] mercury concentrations as ng/g wet weight; dashes indicate no data

Table 9 (cont.): Heavy Metals in Seacumbers from Tanapag Lagoon, Saipan

Species	Site	Location	Tissue[a]	Statistic[b]	Metal (µg/g dry weight)								
					Ag	As[c]	Cd	Cr	Cu	Hg[d]	Ni	Pb	Zn
Holothuria atra	5	CUC Beach	M	mean	nc	1.44	nc	nc	1.42	2.33	nc	1.83	19.9
				range	all <0.12	1.39 - 1.49	all <0.12	all <0.56	1.24 - 1.62	2.09 - 2.60	all <0.22	1.62 - 2.07	17.0 - 23.3
			H	mean	nc	0.75	0.74	0.74	4.74	32.8	0.34	1.61	168
				range	all <0.12	0.73 - 0.77	0.56 - 0.98	<0.53 - 2.04	2.83 - 7.95	29.3 - 36.7	0.32 - 0.35	1.19 - 2.18	100 - 281
	6	Lower Base Channel	M	mean	<0.08	1.92	<0.08	0.69	1.94	2.66	0.20	0.26	17.2
				range	-	-	-	-	-	-	-	-	-
			H	mean	<0.11	1.65	<0.11	0.95	3.79	19.7	0.49	0.54	33.5
				range	-	-	-	-	-	-	-	-	-
	7	Saddok As Agatan	M	mean	nc	0.37	nc	nc	1.56	2.42	nc	0.63	18.7
				range	all <0.10	0.35 - 0.38	all <0.10	all <0.43	1.48 - 1.64	1.90 - 3.07	all <0.18	0.58 - 0.68	18.4 - 19.0
			H	mean	nc	0.82	0.10	0.84	5.26	11.0	nc	0.97	40.6
				range	all <0.09	0.56 - 1.20	<0.09 - 0.24	0.60 - 1.20	3.55 - 7.79	7.82 - 15.4	all <0.16	1.03 - 0.92	29.8 - 55.4
	8	Saddok Dogas	M	mean	nc	0.75	nc	nc	1.60	2.37	nc	nc	17.9
				range	all <0.12	0.71 - 0.80	all <0.12	all <0.51	1.56 - 1.64	1.97 - 2.85	all <0.21	all <0.20	16.6 - 19.4
			H	mean	nc	0.18	0.09	1.61	6.23	24.7	nc	nc	164
				range	all <0.12	0.12 - 0.27	<0.12 - 0.14	0.95 - 2.74	5.57 - 6.96	13.4 - 45.6	all <0.20	all <0.19	129 - 210
	9	Bobo Achugao	M	mean	nc	0.72	nc	nc	1.43	2.47	nc	0.17	18.3
				range	all <0.12	0.38 - 1.36	all <0.12	all <0.50	1.07 - 1.90	2.46 - 2.47	all <0.21	<0.19 - 0.32	16.9 - 19.9
			H	mean	nc	0.54	0.28	2.35	5.68	12.7	0.24	nc	39.7
				range	all <0.23	-	0.23 - 0.34	1.70 - 3.25	4.36 - 7.39	6.14 - 26.3	<0.24 - 0.48	all <0.38	37.4 - 42.2
	10	Plumaria Hotel Beach	M	mean	nc	2.33	nc	nc	1.82	3.94	nc	1.19	21.2
				range	all <0.13	1.04 - 5.23	all <0.13	all <0.53	1.51 - 2.19	3.43 - 4.52	all <0.22	1.01 - 1.40	20.4 - 22.1
			H	mean	nc	0.75	0.35	3.17	4.15	17.8	0.46	1.70	95
				range	all <0.13	0.46 - 1.23	0.34 - 0.36	2.02 - 4.98	3.84 - 4.50	12.6 - 25.2	0.43 - 0.51	1.21 - 2.38	61.1 - 147
	11	San Roque Cemetery Beach	M	mean	nc	14.80	nc	nc	1.41	nc	nc	0.62	20.0
				range	all <0.11	14.3 - 15.4	all <0.11	all <0.45	1.33 - 1.50	all <0.48	all <0.19	0.44 - 0.85	18.2 - 22.6
			H	mean	nc	1.27	0.09	1.56	4.99	25.3	nc	0.96	129
				range	<0.10	0.99 - 1.63	<0.08 - 0.20	1.37 - 1.77	4.55 - 5.46	20.2 - 31.5	all <0 .21	0.85 - 1.09	80.2 - 206
	12	Pau Pau Beach	M	mean	nc	2.59	nc	nc	1.88	2.15	nc	0.34	16.1
				range	all <0.08	2.22 - 3.02	all <0.08	all <0.44	1.4 - 3.10	2.13 - 2.18	all <0.18	0.33 - 0.36	15.2 - 17.0
			H	mean	nc	0.62	nc	0.46	3.49	19.5	0.25	nc	48.5
				range	all <0.25	0.53 - 0.73	all <0.12	<0.41 - 1.05	3.23 - 3.76	12.7 - 29.9	<0.16 - 0.77	all <0.41	41.6 - 56.4

[a] Tissues: M = body wall muscle, H = hemal system; [b] mean as geometric mean (n = 1-2 replicates samples per site); [c] arsenic concentrations as µg/g wet weight; [d] mercury concentrations as ng/g wet weight; dashes indicate no data

Table 10: Heavy Metals in Bivalves from Tanapag Lagoon, Saipan

Species	Site	Location	Statistic[a]	Metal (µg/g dry weight)								
				Ag	As[b]	Cd	Cr	Cu	Hg[c]	Ni	Pb	Zn
Asaphia violascens	2	Puerto Rico Dump	mean	1.15	-	0.66	12.00	44.1	-	6.10	83.5	270
			range	0.99 - 1.32	-	0.62 - 0.70	11.9 - 12.2	26.5 - 73.3	-	5.07 - 7.35	68.1 - 102	220 - 332
Atactodea striata	1	Micro Beach	mean	nc	1.59	0.49	0.46	9.62	15.8	2.64	0.45	120
			range	all <0.25	-	0.49 - 0.50	0.42 - 0.52	8.99 - 10.3	-	2.52 - 2.77	0.34 - 0.60	112 - 129
	8	Saddok Dogas	mean	nc	1.41	1.14	0.69	7.69	15.3	1.91	0.61	105
			range	all <0.23	-	1.14 - 1.15	0.58 - 0.81	7.35 - 8.04	-	1.81 - 2.01	0.51 - 0.74	105 - 106
	9	Bobo Achugao	mean	nc	1.41	5.04	1.97	11.3	17.4	3.26	0.36	127
			range	all <0.24	-	4.66 - 5.45	0.59 - 6.56	9.63 - 13.3	-	2.24 - 4.76	<0.39 - 0.68	109 - 147
	10	Plumaria Hotel Beach	mean	nc	2.19	1.11	0.82	15.4	23.8	2.78	2.94	98.0
			range	all <0.26	-	1.05 - 1.17	0.74 0.91	11.7 - 20.2	-	2.68 - 2.90	2.75 - 3.14	97.3 - 98.7
	11	San Roque Cemetery Beach	mean	2.73	1.21	1.73	0.62	14.0	17.9	3.29	0.95	86
			range	1.47 - 5.08	-	1.55 - 1.93	0.57 - 0.68	13.3 - 14.7	-	3.31 - 3.26	0.95 - 0.96	71.8 - 103
	12	Pau Pau Beach	mean	nc	1.86	0.28	0.91	8.59	8.22	2.62	0.67	101
			range	all <0.21	-	<0.08 - 0.93	0.71 - 1.16	7.95 - 9.29	-	2.61 - 2.63	0.55 - 0.83	92.2 - 110
Gafrarium pectinatum	2	Puerto Rico Dump	mean	0.57	2.64	1.56	1.18	33.7	19.7	11.40	37.5	51.4
			range	0.53 - 0.62	-	1.35 - 1.79	1.06 - 1.31	32.3 - 35.3	-	10.9 - 12.0	31.4 - 44.9	47.7 - 55.3
	3	Echo Bay	mean	0.34	3.41	1.03	0.65	17.8	14.2	12.2	50.4	52.3
			range	0.31 - 0.38	-	1.00 - 1.07	0.64 - 0.65	16.7 - 18.9	-	11.5 - 13.0	46.9 - 54.2	45.9 - 60.7
	5	CUC Beach	mean	0.14	4.42	0.95	0.58	11.70	23.3	12.2	37.6	55.8
			range	<0.14 - 0.28	-	0.69 - 1.31	0.58 - 0.59	8.34 - 16.3	-	10.6 - 14.1	30.2 - 46.7	49.7 - 62.6
	6	Lower Base Channel	mean	nc	2.71	0.81	0.83	7.97	9.91	13.1	8.31	51.7
			range	all <0.24	-	0.78 - 0.84	0.82 - 0.84	6.69 - 9.50	-	12.8 - 13.4	7.97 - 8.67	42.3 - 63.2
Ctena bella	1	Micro Beach	mean	0.51	0.92	1.77	0.87	8.64	22.0	4.95	6.16	406
			range	0.33 - 0.81	-	1.16 - 2.71	0.82 - 0.92	5.31 - 14.1	-	5.57 - 4.40	5.94 - 6.38	384 - 430
Quidnipagus palatum	2	Puerto Rico Dump	mean	2.70	2.57	0.19	6.34	419	111	8.88	63	614
			range	1.46 - 4.65	-	0.16 - 0.21	4.46 - 8.60	284 - 581	-	7.30 - 12.5	24.2 - 148	324 - 1027
	2	Puerto Rico Dump[d]	mean	18.1	-	0.30	9.70	1389	-	10.1	172	720
			range	10.9 - 24.1	-	0.28 - 0.37	7.38 - 10.6	866 - 1876	-	8.94 - 11.3	163 - 184	605 -993
	3	Echo Bay	mean	1.86	3.24	1.40	8.59	341	56.6	8.32	117	305
			range	-	-	-	-	-	-	-	-	-
	5	CUC Beach	mean	0.90	1.67	0.24	4.94	105	33.6	13.0	80.0	724
			range	0.89 - 0.91	-	0.22 - 0.26	4.81 - 5.07	104 - 106	-	12.9 - 13.1	75.8 - 84.3	530 - 990
	6	Lower Base Channel	mean	0.49	3.42	0.20	6.15	23.7	44.3	11.6	13.3	501
			range	0.32 - 0.74	-	0.19 - 0.21	4.86 - 7.76	14.7 - 38.2	-	11.4 - 11.7	9.01 - 19.7	478 - 525
Pinna fragilis	6	Saddok Dogas	mean	1.06	-	13.1	2.86	11.5	-	48.4	2.29	1051
			range	-	-	-	-	-	-	-	-	-

[a] Mean as geometric mean; [b] arsenic as ug/g wet weight; [c] mercury concentrations as ng/g wet weight; [d] a second collection was made closer to the shoreline than the first; nc = not calculable; dashes indicate no data

Table 11: Heavy Metals in Juvenile Fish from Tanapag Lagoon, Saipan

Species	Site	Location	Length (cm)	Statistic[a]	Metal (µg/g wet wt.)	
					As	Hg[b]
Caranx sexfasciatus	1	Micro Beach	11.5 - 12.0	mean	6.21	17.9
				range	-	-
	1	Puerto Rico Dump	12.0	mean	4.43	71.8
				range	-	-
	4	Sea Plane Ramps	12.0 - 13.5	mean	16.9	32.0
				range	-	-
	6	Lower Base Channel	14.5 - 17.0	mean	1.33	27.1
				range	0.81 - 2.20	27.1 - 27.2
	7	Saddok As Agatan Beach	12.5	mean	1.60	40.2
				range	-	-
Gerres argyreus	1	Micro Beach	9.5 - 10.5	mean	2.14	6.6
				range	-	-
	2	Puerto Rico Dump	10.0	mean	17.4	70.8
				range	-	-
	3	Echo Bay	10.5 - 17.0	mean	7.53	55.1
				range	4.6 - 19.2	18.7 - 97.4
	4	Sea Plane Ramps	13.0	mean	5.22	34.9
				range	-	-
	5	CUC Beach	10.5 - 11.5	mean	18.8	17.1
				range	-	-
	6	Lower Base Channel	9.0 - 13.0	mean	20.1	16.8
				range	13.3 - 28.1	12.3 - 41.0
	7	Saddok As Agatan	12.5 - 16.0	mean	17.0	21.6
				range	7.60 - 37.9	19.0 - 24.6
	8	Saddok Dogas	10.0 - 14.0	mean	15.7	19.7
				range	10.1 - 37.9	14.4 - 37.4

[a]mean as geometric mean (n = 1-3 fish deepending on size and species); [b]mercury concentrations as ng/g wet weight; dashes indicate no data

Table 11 (cont.): Heavy Metals in Juvenile Fish from Tanapag Lagoon, Saipan

Species	Site	Location	Length (cm)	Statistic[a]	Metal (µg/g wet wt.)	
					As	Hg[b]
Mulloides vanicolensis	1	Micro Beach	9.0 - 12.5	mean	3.10	4.72
				range	-	3.16 - 6.10
	2	Puerto Rico Dump	11.0 - 12.5	mean	10.7	16.6
				range	-	-
	3	Echo Bay	8.5 - 14.0	mean	3.7	20.8
				range	1.41 - 20.8	5.27 - 42.7
	4	Sea Plane Ramps	9.0 - 15.5	mean	5.7	18.3
				range	3.44 - 9.81	14.4 - 22.7
	6	Lower Base Channel	13.0 - 15.5	mean	4.84	12.7
				range	3.83 - 6.11	10.2 - 15.9
	7	Saddok As Agatan	14.0 - 18.0	mean	6.31	14.0
				range	4.52 - 8.90	13.1 - 19.9
	8	Saddok Dogas	9.0 - 14.0	mean	3.47	9.22
				range	2.8 - 4.24	5.13 - 13.0
	9	Bobo Achugao	11.5 - 16.0	mean	8.43	23.4
				range	5.01 - 29.9	14.8 - 35.7
	10	Plumaria Hotel Beach	9.0 - 10.0	mean	1.33	6.92
				range	1.21 - 1.43	5.40 - 8.86
	11	San Roque Cemetery Beach	9.5 - 14.0	mean	6.53	16.4
				range	4.52 - 10.3	4.08 - 35.2
	12	Pau Pau Beach	8.5 - 17.5	mean	4.52	9.78
				range	2.26 - 7.34	3.11 - 24.9
Valamugil engeli	1	Micro Beach	8.5 - 15.0	mean	1.32	8.74
				range	0.34 - 2.44	-
	2	Puerto Rico Dump	9.0 - 14.0	mean	7.91	33.6
				range	1.81 - 23.3	12.4 - 74.8
	3	Echo Bay	9.0 - 13.0	mean	2.01	26.3
				range	1.61 - 2.27	18.4 - 37.0
	4	Sea Plane Ramps	10.5 - 12.0	mean	1.45	11.3
				range	-	-
	5	CUC Beach	9.0 - 10.0	mean	2.36	13.2
				range	-	-
	6	Lower Base Channel	9.5 - 14.0	mean	0.94	15.1
				range	0.29 - 1.48	8.80 - 25.1

[a]mean as geometric mean (n = 1-6 fish deepending on size and species); [b]mercury concentrations as ng/g wet weight; dashes indicate no data

CONCLUSIONS AND RECOMMENDATIONS

This investigation, though preliminary in nature, adds significantly to the contaminant database for Saipan's coastal waters. It clearly identifies areas of contaminant enrichment within biotic components of Tanapag Lagoon and provides a useful database with which future levels can be compared and evaluated. In addition, the survey has identified a number of potentially useful bioindicator organisms for future monitoring purposes and has assessed their current contamination status by reference to levels found in similar and related species from other parts of the world.

The study confirmed previous findings of trace metal enrichment in surface sediments around the base of the Puerto Rico Dump. Levels of copper, lead and zinc measured here were at least two orders of magnitude higher than the lowest values determined elsewhere in the lagoon, while values for cadmium, chromium, mercury and nickel were at least one order of magnitude higher. Evidence is also presented that clearly shows this enrichment is being transmitted to biotic components in the area although the implications from the data are that natural processes operating in the sediments and overlying water column place some constraints on rates of transfer. The role of iron and manganese in regulating metal recycling processes in aquatic environments is well known (Förstner and Wittmann 1983) and undoubtedly of primary importance here considering that both elements are typically high in leachate streams emerging from municipal dumps (Denton *et al.* 2005b). Likewise, the complexation of free metal ions with dissolved organic ligands, released from decomposing organic wastes in the dump, coupled with dilution and dispersion processes associated with the continual tidal flushing in and out of the area, all serve to keep the biologically available metal fraction in the water column close to baseline. This was clearly demonstrated by the algae and bivalves analyzed from this location.

Thus, metal contaminants released from the dump become predominantly entrained in the surrounding sediments and have little impact on the dissolved metal fraction in the water column. They accumulate in this environmental compartment over time and can only be mobilized out of the area by forces that physically disturb the bottom deposits, e.g., typhoons, storm surges, dredging activities. Likewise, movement of contaminant metals into biotic communities within the area will occur via the suspension feeder-carnivore route rather than through primary producers and secondary trophic level consumers. The fact that herbivorous fish from this area are not overly burdened with Hg, despite relatively high levels of this element in surface sediments lends support to this hypothesis (Denton and Trianni in prep.).

The bioindicator capabilities of the organisms studied during the present investigation varied between species in a metal dependant fashion (Table 12). Compared with algae, the seagrass, *Enhalus acaroides*, is an impressive indicator of dissolved copper levels but is relatively insensitive to changes in the ambient availability all other elements examined. Seacucumbers have little control over cadmium, copper, mercury and lead concentrations in their hemal system but are able to regulate most other metals considered here, with the possible exception of arsenic (Denton *et al.* 1999). Of the bivalves examined, *Quidnipagus palatum*, stands apart from the rest on several accounts. First and foremost, it is particularly sensitive to ambient changes in available silver, cadmium, chromium, copper, mercury, lead and zinc in sediments. It is also readily identifiable, easy to collect and relatively common in the muddy sands and gravel

Table 12: Summary of Trace Element Bioindicator Potential of Organisms Studied

Species	Metal Fraction Reflected	Ag	As	Cd	Cr	Cu	Hg	Ni	Pb	Zn
Algae										
Padina spp.	Dissolved metals in overlying water	✓	✓	✓	✓	✓✓	✓	✓	✓✓	✓✓
Sargassum spp.	column	✓	✓	✓	✓	✓✓	✓	✓	✓✓	✓✓
Seagrass										
Enhalus acaroides	Dissolved metals in water column and	?	?	✓	?	✓✓	?	x	✓	✓
Halodule uninervis	sediment pore waters	?	?	✓	?	✓✓	?	x	✓	✓
Seacucumbers										
Holothuria atra	Primarily sediment and particulate									
body wall	bound metals taken up via the	?	✓	x	x	x	x	x	✓	x
hemal system	ingestion of bottom deposits	?	✓	✓	x	✓	✓	x	✓	x
Bivalves										
Asaphia violascens	Dissolved and particulate bound	✓	?	✓	✓✓	✓	?	x	✓✓	✓
Atactodea striata	metals filtered out of the overlying		?	?	?	?	?	x	?	?
Ctenna bella	water column, in addition to soluble	✓	x	?	✓	?	?	x	?	✓
Gafrarium pectinatum	metals in sediment pore waters	✓	?	?	✓	✓	?	x	✓✓	x
Quidnipagus palatum		✓✓	x	✓	✓✓	✓✓	✓	x	✓✓	✓✓
Fish										
Mulloides varicolensis	Primarily derived from food	x	?	x	x	x	✓✓	x	x	x

Bioindicator capability: ✓✓ = highly sensitive usually with high affinity; ✓ = reasonably sensitive but may not have high affinity; X = very weak to none responsive; ? = unknown

deposits of low energy beaches throughout the region. Such sheltered areas frequently tend to be impacted by the activities of man which makes this species ideally positioned for monitoring purposes. Lastly, mature specimens are large enough to provide adequate tissue for conventional metal analysis. Its only limitation as a monitoring tool lies in its often patchy distribution and its apparent insensitivity to arsenic and nickel.

As in this study, algae and bivalve bioindicators are frequently employed together to differentiate between soluble and particulate metal loads in the water column. Incorporating a rooted macrophyte like seagrass into a monitoring program has the added advantage of reflecting trace metal contributions from sediment pore waters, while seacucumbers mirror those derived principally from the ingestion of bulk sediments. Used appropriately, these organisms broaden the scope of monitoring programs designed to identify the distribution and abundance of heavy metals in aquatic environments.

A final comment is reserved here for changes noted in the edible quality of fisheries resources harvested in the lagoon. Such resources include various species of algae, seacucumbers (body wall only), bivalve mollusks and fish. Many countries of the world have established standards for trace metals in seafood (Nauen 1983). Food standards in the U.S. are under the jurisdiction of the U.S. Food and Drug Administration (FDA) with non-regulatory technical guidance provided by the U.S. Environmental Protection Agency. Currently, the only enforceable metal standard is for mercury. The 'action level' for this element presently stands at 1.0 µg/g wet weight for organic (methyl) mercury rather than total mercury. None of the organisms analyzed here exceeded this value.

A series of non-enforceable guidelines also exist in the U.S. for arsenic (total), cadmium, chromium, nickel and lead in shellfish. The applicable guidelines for bivalves are 84, 4, 13, 80 and 1.7 µg/g wet weight, for each metal respectively (USFDA 1998). Based on these standards, lead clearly stands out as the element of greatest concern with excedences noted in all bivalve species collected near the dump (site 2), Echo Bay (site 3) and CUC Beach (site 5). Levels in *Q. palatum* were especially high and averaged around 35, 25 and 15 µg/g wet weight at each site respectively. The only other element of potential concern is copper which was detected at levels in excess of 300 µg/g wet weight in *Q. palatum* collected near the dump. While there are no current U.S. standards for copper in seafood, those in effect in other countries of the world range from 10-100 µg/g wet weight (Nauen 1983). Trace metal levels in algae and the edible portion of seacucumbers within the lagoon were all well below critical threshold levels of concern.

It is hoped that the study described herein will serve as a catalyst for more detailed investigations of spatial and temporal trends in contaminant levels for all of Saipan's nearshore waters and representatives of the biotic communities that inhabit them. Such data is imperative if we are to achieve sustainability of these fragile coastal ecosystems and preserve the integrity of their component flora and fauna, especially those that are harvested for human consumption. To this end, a major survey of contaminant levels (arsenic, mercury and PCBs) in adult food fish from within Tanapag Lagoon has recently been completed (Denton and Trianni, in prep) and our nearshore monitoring and assessment program extended into the two lagoonal entities immediately to the south. The findings of these investigations will be published in due course.

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Plate 9: Saipan's new state-of-the-art solid waste facility in Marpi, at the northern end of the island, was opened in February 2003.