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Baseline

The impact of a rudimentary landfill on the trace metal status of Pago Bay, Guam

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Pago Bay, one of several prominent bays along the south-eastern coastline of Guam, is a windward fringing reef flat located at 13°28'18.68"N, 144°47'14.85"E (Fig. 1). It is approximately 3 km long, 0.75 km at its widest point, and covers an area of around 1.5 km^2. A narrow, shallow-water moat extends along the inner edge of the bay, adjacent to the coastline. This gives way to an extensive reef flat, and a reef margin characterized by a well-developed spur and grove formation (Randall and Holloman, 1974). Bottom substrates within the bay range from soft alluvial mud around the river mouth at the southern end, to coarse carbonate sands and coral rubble further north. The bay harbours a relatively rich diversity of marine life and supports a variety of scientific, commercial and recreational activities, including harvesting by local residents of many of its fisheries resources for food.

Pago Bay receives continuous drainage from the Pago River system, a complex of three rivers that drains a catchment area of approximately 27 square kilometres inland. One of these rivers, the Lonfit River, receives leachate from the island's only municipal landfill located in the village of Ordot, about 3.5 km upstream of the estuary. The Ordot landfill has been in continuous use for over 50 years and receives about 75 m^3 of solid waste per day (GEPA, 1995). Slated for closure over 25 years, it now occupies an area of almost 25 ha and towers to ~90 m at its mid-point (Smit, 2001). The landfill is unlined and does not have a leachate retention system in place. As a consequence, seasonally dependant streams of brown, foul smelling liquid emerge at a number of points along the western edge and southern toe of the facility. These flow down gradient into the Lonfit River and eventually make their way out into Pago Bay.

Chemical characterization of the leachate streams and the receiving waters of the Lonfit River have identified trace (heavy) metals as the contaminants of primary concern from an ecological and human health perspective (USEPA, 2002; Denton et al., 2005a). Specific elements flagged as exceeding toxicity thresholds in the leachate included arsenic, cadmium, chromium, copper, iron, lead, manganese, mercury, nickel, silver and zinc (USEPA, 2002). Metals mobilized from the landfill tend to accumulate in sediments of the leachate streams under low stream flow conditions and are periodically swept downstream into Pago Bay during major storm events (Denton et al., 2007). The impact of such episodic inputs on the sediment chemistry and biological resources of this environmentally sensitive area have never been investigated despite some considerable speculation by concerned members of the local community. The study described herein is the first of its kind to address these issues.

The Pago River drains into the southern half of Pago Bay and is highly seasonal. The river has formed a channel that cuts completely though the reef flat and drains much of the water coming over the reef margin at high tide back into the ocean. Sedimentary deposits within the bay are largely confined to the moat and intertidal zone and are virtually absent on much of the reef flat. The composition of these deposits varies appreciably within the bay, with surface sediments at the north-eastern end composed largely of bioclastic (biogenic) carbonates (e.g., foraminifera, coral, shells, *Halimeda* debris and calcareous red algae) while volcanic detrital material predominates at the south-eastern end, adjacent to the river mouth (Randall and Holloman, 1974). A mixture of the two sediment types occurs to varying degrees in between. Currently, conspicuous banks of silt and clay have accumulated in the intertidal zone on both sides of the river mouth as a result of soil erosion processes further upstream. The extent of deposition of this material is controlled largely by rain events, which also play a significant role in purging the bay of accumulated sediments when major storms occur. Groundwater seepage occurs at various points along the beach north of the river mouth for ~1.5 km and a major spring discharges into the bay ~200 m south of the river mouth. During the wet season, the central part of the bay is heavily inundated with urban runoff from a nearby residential area. The northern part of the bay also receives runoff and septic system wastes from the lower University of Guam campus.

Biota are unevenly distributed throughout the bay. At the time of this study, conspicuous patches of seagrass (*Enhalus acoroides*) occurred in the muddy moat sediments on both sides of the river channel in the southern half of the bay and provided a suitable habitat for several species of bivalves including *Ctena bella*, *Gafrarium pectinatum,* and *Quidnipagus palatum*. Of the common brown algae encountered, *Sargassum cristafolium* dominated the outer reef flat along the entire length of the reef margin, while *Padina boryana* was the most abundant species in the moat area, where the seacucumber, *Holothuria atra*, was also reasonably well represented.

Sediments were collected from Pago Bay in January 2005. Sampling sites were located at ~100 m intervals along the beach and at ~100–200 m intervals along five transect lines running perpendicular to the shore (Fig. 1). In all, 40 sampling sites were selected for study although sites 1–3 and 32 were subsequently found to have

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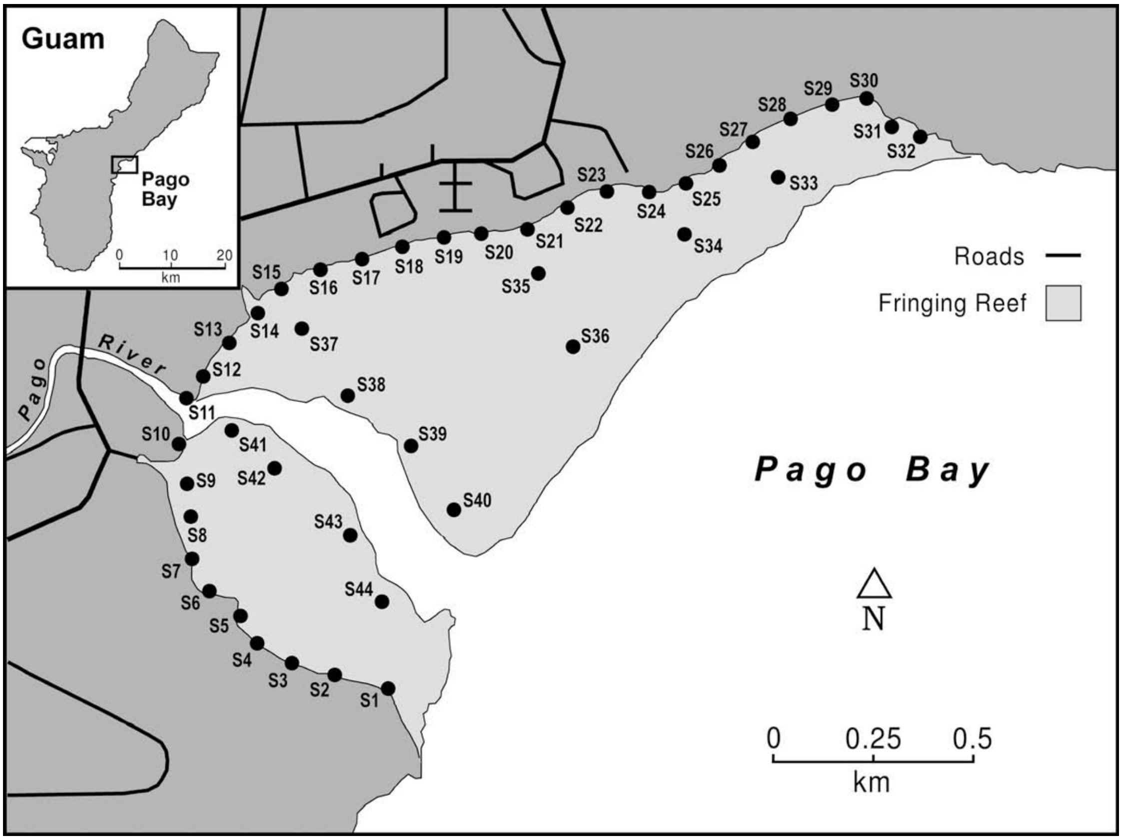

Fig. 1. Sediment sampling sites in Pago Bay, Guam.

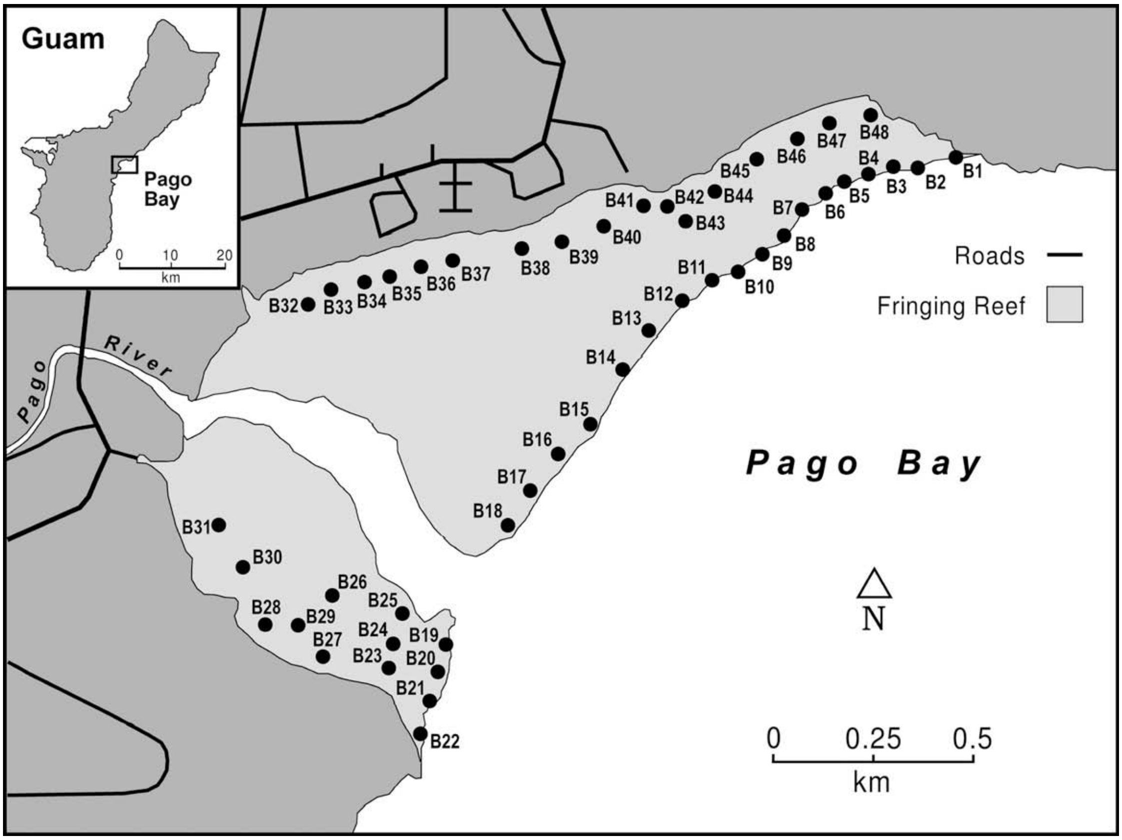

Fig. 2. Biota sampling sites in Pago Bay, Guam.

no unconsolidated material. The precise location of each sampling site was recorded using GPS. Samples ($\sim$100 g) were gently scooped up in acid-washed plastic containers so as not to disturb surface layers. Three separate samples were taken within a $\sim$3 m diameter circle at each site. In the laboratory, all samples were dried at either $\sim$30 °C (arsenic and mercury analyses) or $\sim$60 °C (all other metals) and sieved through a 1 mm Teflon screen in preparation for analysis.

Biota samples were collected at low tide from 48 sites in the bay between June and September 2005 (Fig. 2). Emphasis was placed on collecting species with established or potential bioindicator capability as well as those traditionally harvested by local residents for food. As can be seen from Table 1, not all species were available at all sites. All specimens were handpicked from the reef flat and transported to the laboratory in clean polyethylene bags and buckets. 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 storage at -20 °C. Subsequently, the entire soft parts of thawed specimens were taken for analysis. 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 portions of the hemal system were separated out for analysis from these organisms. All cleaned and separated samples were placed in acid-washed, polypropylene vials (80 mL). The analyses were performed on samples dried to constant weight at 60 °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 samples were analysed for trace metals by atomic absorption spectroscopy (AAS) following conventional wet oxidation in hot nitric acid. The procedure was essentially similar to USEPA method 3050A, SW-846 (USEPA, 1996) with minor modifications as outlined in Denton et al. (2005b). It was designed specifically to release weakly to strongly bound metals in the sample without completely destroying the mineral matrix of non-carbonate components in the sample and is particularly useful for identifying metal enrichment as a result of anthropogenic activities. Mercury was analysed by cold vapour AAS, arsenic by hydride generation, and the other metals by flame AAS. Simultaneous corrections for non-atomic absorption, where applicable, were made by the instrument (deuterium lamp). Mercury calibration standards (5–20 μg/l) were made up in 10% nitric acid with 0.05% potassium dichromate as a preservative (Feldman, 1974). All other 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). The procedures for biota analyses were essentially the same as 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 for 3 h at 100 °C in 2:1 nitric and sulfuric acids rather than nitric acid alone, a more powerful oxidizing mixture being required for the rapid destruction of organic matter in the wet tissues. Finally, samples for all other metals were subjected to two 3 h digestion/drying cycles at 135 °C with hot nitric acid prior to topping up to final volume with 10% nitric acid.

Quality assurance procedures included the use of analytical grade reagents, method blanks and matrix spikes. Approximately 10% of the samples were run in duplicate. All plastic and glassware were acid-washed and deionized water rinsed prior to use, and standard stock solutions were purchased from a commercial supplier. Trace metal recoveries from certified standard reference materials were within acceptable limits for all elements examined (Tables 2 and 3).

Table 1
Flora and fauna of Pago Bay sampled in the present study

Species	Biota sites
Algae	
Acanthophora spicifera	39, 41, 42, 46, 47
Gracilaria salicornia	42, 48
Caulerpa rasemosa	10
Caulerpa serrulata	44
Caulerpa sertalarioides	48
Chlorodesmis fastigiata	21
Padina boryana	27, 28, 42, 44, 45, 47
Turbinaria ornata	26, 40, 41, 43, 45, 47
Sargassum cristafolium	1, 2 , 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, *22*
Sargassum polycystum	23, 24, 25, 37, 39, 40, 41, 42
Seagrass	
Enhalus acoroides	29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 41
Seacucumber	
Holothuria atra	4, 6, 12, 13, 16, 17, 19, 20, 22,
Bivalves	
Asaphia violascens	48
Ctena bella	31, 34, 36, 37
Gafrarium pectinatum	34
Quidnipagus palatum	29, 31, 36, 48,
Scutarcopajia scobinata	36

Table 2
Recovery of trace metals (μg/g dry wt) from a standard soil reference material

Metal	This study		Certified values	
	Mean	Range	Mean	Range
PriorityPollutnT^{TM}/CLP inorganic soils (Catalog No. PPS-46; Lot No. 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
Iron	9110	7324–12654	8610	3760–13500
Lead	54.6	45.2–61.9	56.6	43.1–70.1
Manganese	1252	1134–1463	1310	1010–1610
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 3
Recovery of trace metals (μg/g dry wt) from biota standard reference materials

Metal	Mean ± 95% Confidence limits	
	This study	Certified values
Apple leaves (SRM 1515)		
Cadmium	0.03 ± 0.005	0.013 ± 0.002
Chromium	0.36 ± 0.084	0.3 (Not certified)
Copper	5.17 ± 0.26	5.64 ± 0.24
Iron	61.9 ± 2.10	83 ± 5
Lead	0.32 ± 0.002	0.47 ± 0.02
Manganese	47.0 ± 2.15	54 ± 3
Nickel	0.95 ± 0.08	0.91 ± 0.12
Silver	0.05 ± 0.006	No data
Zinc	12.1 ± 0.50	12.5 ± 0.03
Albacore tuna (RM 50)		
Arsenic	2.47 ± 0.07	3.3 ± 0.4
Mercury	1.04 ± 0.04	0.95 ± 0.1

Table 4
Strone acid extractable trace metals (µg/g dry wt) in surface sediments from Pago Bay Guam

Site	Statistic[a]	Ag	As	Cd	Cr	Cu	Fe	Hg[b]	Mn	Ni	Pb	Zn
4 (a–c)	mean	nc	0.86	nc	7.39	10.1	3,848	6.26	140	4.46	14.4	8.18
	range	all < 0.15	0.74–1.01	all < 0.15	6.71–7.87	8.19–12.0	3,603–4,203	5.85–6.67	128–153	4.28–4.80	14.2–14.6	8.04–8.29
5 (a–c)	mean	nc	1.28	nc	9.61	13.2	6,138	9.30	144	8.48	7.65	11.3
	range	all < 0.15	0.81–2.39	all < 0.15	7.08–12.8	10.2–15.3	5,417–6,627	8.53–10.4	135–158	7.61–9.66	4.68–10.3	10.3–12.5
6 (a–c)	mean	nc	1.43	nc	6.44	5.76	3,990	6.39	131	4.98	3.71	9.24
	range	all < 0.15	1.04–1.77	all < 0.15	5.39–8.39	4.16–8.53	2,762–6,737	4.96–7.80	124–145	2.81–8.82	3.40–4.37	6.98–14.8
7(a–c)	mean	nc	1.60	nc	14.1	17.5	20,533	12.4	453	21.7	1.85	28.0
	range	all < 0.15	0.91–2.15	all < 0.15	13.6–14.9	17.1–18.1	19,394–22,119	10.8–15.0	431–498	17.7–24.2	1.56–2.17	25.7–30 7
8 (a–c)	mean	nc	1.56	nc	14.4	14.9	17,330	13.6	421	22.1	1.60	28.4
	range	all < 0.15	1.40–1.82	all < 0.15	13.2–16.9	14.4–15.3	16,818–17,958	10.6–18.0	386–457	21.2–22.7	0.94–4.67	27.7–29.6
9 (a–c)	mean	nc	0.98	nc	9.64	7.76	9,938	7.97	293	13.3	nc	14.0
	range	all < 0.15	0.81–1.10	all < 0.15	8.21–11.0	6.30–9.00	8,098–11,874	7.08–9.16	280–316	11.1–15.6	all < 0.31	10.8–17.5
10 (a–c)	mean	nc	0.14	nc	21.1	6.45	41,743	4.34	430	15.0	4.41	65.3
	range	all < 0.15	0.07–0.33	all < 0.15	15.9–25.6	5.70–7.20	27,504–52,278	3.28–7.46	319–533	13.1–17.0	1.25–20.5	36.6–89.5
11 (a–c)	mean	nc	0.78	nc	10.9	9.51	12,184	7.37	265	14.8	1.10	19.0
	range	all < 0.15	0.68–0.95	all < 0.15	10.5–11.2	8.29–10.5	11,276–12,834	7.00–8.08	225–296	13.0–16.1	0.93–1.54	17.6–19.8
12 (a–c)	mean	nc	0.53	nc	7.70	6.73	8,653	4.64	216	10.4	nc	11.3
	range	all < 0.15	0.34–0.76	all < 0.15	7.49–7.88	6.58–6.80	8,434–8,992	3.27–6.25	197–229	9.65–11.1	all < 0.27	10.7–11.9
13 (a–c)	mean	nc	0.56	nc	7.78	8.04	9,119	5.70	211	11.2	nc	13.0
	range	all < 0.15	0.50–0.66	all < 0.15	7.37–8.62	7.12–9.40	7,873–10,986	4.48–7.15	193–223	10.0–13.4	<0.25–0.88	12.2–14.3
14 (a–c)	mean	nc	1.17	nc	5.67	6.15	6,333	4.32	117	7.66	nc	10.2
	range	all < 0.15	0.86–1.36	all < 0.15	5.52–5.95	5.58–6.63	6,273–6,392	4.10–4.64	109–129	6.37–9.88	<0.26–0.53	9.96–10.4
15 (a–c)	mean	nc	1.14	nc	3.71	3.01	2,400	3.95	64.5	2.46	nc	5.61
	range	all < 0.15	0.91–1.36	all < 0.15	3.38–4.07	2.37–3.45	1,923–2,733	3.56–4.66	55.2–70.0	1.70–3.20	<0.24–0.76	4.60–6.21
16 (a–c)	mean	nc	0.57	nc	4.10	1.90	2,026	5.27	82.4	2.07	nc	4.13
	range	all < 0.15	0.49–0.72	all < 0.15	3.35–4.78	1.58–2.33	1,643–2,276	3.65–8.78	62.7–118	1.58–2.89	<0.25–0.48	3.70–4.80
17 (a–c)	mean	nc	0.51	nc	3.59	1.82	1,373	3.79	102	1.63	nc	4.41
	range	all < 0.15	0.47–0.57	all < 0.15	3.27–3.90	1.42–2.39	1,191–1,735	3.53–4.20	98.4–109	1.58–1.66	all < 0.26	3.69–5.98
18 (a–c)	mean	nc	0.50	nc	4.28	1.96	1,871	3.07	134	2.01	nc	3.44
	range	all < 0.15	0.41–0.74	all < 0.15	3.57–5.34	1.83–2.18	1,604–2,197	2.48–3.47	111–169	1.29–3.39	all < 0.25	3.24–3.77
19 (a–c)	mean	nc	0.54	nc	7.97	4.60	4297	3.45	221	4.85	0.63	6.99
	range	all < 0.15	0.42–0.74	all < 0.15	5.9–10.4	2.77–8.53	3,766–4,728	2.87–3.84	136–340	3.00–8.94	0.47–0.75	3.74–17.2
20 (a–c)	mean	nc	0.82	nc	15.8	7.83	9,115	6.59	244	7.25	nc	8.33
	range	all < 0.15	0.66–0.92	all < 0.15	15.4–16.1	5.48–9.86	7,560–10,393	5.86–7.92	159–382	4.58–9.88	<0.25–0.48	7.11–9.30
21 (a–c)	mean	nc	0.68	nc	12.0	5.13	6,444	6.11	218	6.84	0.88	6.77
	range	all < 0.15	0.54–0.81	all < 0.15	11.1–12.9	4.89–5.25	6,197–6,576	5.21–7.18	178–304	5.04–11.1	<0.24–4.06	6.00–7.95
22 (a–c)	mean	nc	0.67	nc	7.37	3.73	3,353	6.56	144	4.01	0.76	4.35
	range	all < 0.15	0.55–0.87	all < 0.15	5.95–8.41	3.33–4.37	2,518–4,160	5.23–8.91	120–203	3.10–5.59	0.46–1.02	4.02–4.67
23 (a–c)	mean	nc	0.79	nc	12.1	8.37	6,901	7.78	434	10.1	0.70	11.6
	range	all < 0.15	0.68–0.97	all < 0.15	11.3–13.3	7.30–9.64	6,340–8,064	6.94–8.43	369–474	9.00–12.2	0.50–0.93	8.30–20.3
24 (a–c)	mean[b]	nc	0.26	nc	4.03	1.34	932	4.33	36.7	1.23	0.62	1.54
	range	all < 0.15	0.25–0.28	all < 0.15	3.29–4.61	1.19–1.53	893–973	3.43–5.39	33.1–40.1	0.77–1.68	0.47–1.01	1.34–1.77
25 (a–c)	mean	nc	0.29	nc	2.33	0.85	228	3.21	15.2	0.45	0.65	0.95
	range	all < 0.15	0.24–0.35	all < 0.15	2.06–2.52	0.72–1.15	206–256	2.72–3.54	14.8–15.9	0.45–0.46	0.51–0.73	0.75–1.15
26 (a–c)	mean	nc	0.20	nc	2.22	0.84	388	4.45	13.4	0.79	0.40	0.77
	range	all < 0.15	0.12–0.39	all < 0.15	1.94–2.64	0.73–0.90	279–600	3.45–7.08	12.2–14.7	0.60–1.08	0.25–0.51	0.60–1.05
27(a–c)	mean	nc	0.16	nc	2.13	0.72	231	2.98	12.0	nc	nc	0.77
	range	all < 0.15	0.09–0.44	all < 0.15	2.07–2.22	0.59–0.86	200–261	2.63–3.60	11.6–12.4	<0.16–0.32	all < 0.25	0.71–0.88
28 (a–c)	mean	nc	0.25	nc	1.96	0.68	275	3.88	11.4	0.59	0.50	0.93
	range	all < 0.15	0.22–0.27	all < 0.15	1.76–2.21	0.57–0.75	238–298	3.52–4.45	10.9–11.8	0.31–0.82	0.48–0.51	0.85–1.05
29 (a–c)	mean	nc	0.38	nc	1.97	1.16	315	3.28	10.9	nc	0.70	1.34
	range	all < 0.15	0.23–0.51	all < 0.15	1.86–2.09	0.72–2.64	278–337	2.70–3.62	10.3–11.4	<0.15–0.31	0.50–0.94	1.15–1.79
30 (a–c)	mean	nc	0.27	nc	2.68	1.32	579	8.52	30.2	0.82	3.19	6.89
	range	all < 0.15	0.23–0.36	all < 0.15	2.48–2.92	1.23–1.47	379–1,125	7.78–8.97	29.4–30.9	0.75–0.92	1.90–5.23	4.35–12.2
31 (a–c)	mean	nc	0.26	nc	3.36	1.78	1,055	11.9	31.7	1.30	2.48	12.4
	range	all < 0.15	0.25–0.27	all < 0.15	2.84–3.93	1.59–2.21	993–1,148	10.1–15.7	31.1–32.3	1.10–1.80	2.20–2.96	7.57–16.6
33 (a–c)	mean	nc	0.36	nc	4.03	0.69	277	3.22	13.7	1.68	nc	0.96
	range	all < 0.15	0.18–0.55	all < 0.15	3.61–4.32	0.61–0.85	243–310	1.66–6.14	12.4–15.5	1.46–1.83	<0.25–0.99	0.85–1.13
34 (a–c)	mean[b]	nc	0.25	nc	3.76	0.60	203	1.74	18.7	1.65	0.47	0.76
	range	all < 0.15	0.10–0.56	all < 0.15	3.63–4.00	0.56–0.64	148–311	1.65–1.79	13.3–22.8	1.57–1.73	<0.26–0.74	0.62–1.14
35 (a–c)	mean	nc	0.26	nc	4.44	0.86	410	1.56	18.1	1.95	nc	0.86
	range	all < 0.15	0.24–0.30	all < 0.15	4.18–4.91	0.83–0.90	309–510	0.83–2.62	16.5–19.2	1.83–2.08	all < 0.26	0.80–0.92

(*continued on next page*)

Table 4 (*continued*)

Site	Statistic[a]	Ag	As	Cd	Cr	Cu	Fe	Hg[b]	Mn	Ni	Pb	Zn
36 (a–c)	mean	nc	0.25	nc	3.80	0.97	464	3.67	21.7	1.92	nc	0.94
	range	all < 0.15	0.16–0.47	all < 0.15	3.60–3.96	0.82–1.08	360–593	3.28–4.17	19.6–23.1	1.75–2.12	<0.26–0.53	0.79–1.10
37 (a–c)	mean	nc	0.21	nc	5.94	1.58	861	2.39	39.9	2.24	0.36	1.46
	range	all < 0.15	0.13–0.31	all < 0.15	4.28–9.05	1.24–2.33	551–1,947	1.76–2.85	37.8–42.5	1.93–2.97	0.25–0.73	1.06–2.58
38 (a–c)	mean	nc	0.35	nc	4.57	1.61	914	1.55	46.1	2.29	nc	1.64
	range	all < 0.15	0.25–0.44	all < 0.15	4.37–4.87	1.43–1.98	731–1,232	0.81–2.67	40.0–49.6	2.01–2.54	all < 0.26	1.27–2.66
39 (a–c)	mean	nc	0.35	nc	3.76	1.06	522	1.67	41.9	2.03	nc	1.32
	range	all < 0.15	0.26–0.50	all < 0.15	3.60–3.92	0.96–1.20	397–671	1.62–1.71	40.3–43.0	1.98–2.11	<0.25–0.52	1.09–1.72
40 (a–c)	mean	nc	0.39	nc	4.05	1.23	790	1.92	73.3	2.41	nc	1.50
	range	all < 0.15	0.34–0.43	all < 0.15	3.85–4.16	1.09–1.44	642–998	1.63–2.55	70.6–77.4	2.18–2.67	<0.26–0.50	1.27–1.83
41 (a–c)	mean	nc	0.46	nc	14.5	19.9	24,316	12.4	441	25.4	nc	25.4
	range	all < 0.15	0.37–0.58	all < 0.15	13.3–15.4	19.6–20.3	23,465–25,014	11.5–13.4	418–464	24.9–26.0	all < 0.26	25.0–26.2
42 (a–c)	mean	nc	0.61	nc	6.75	7.88	5,637	9.70	243	9.61	nc	9.65
	range	all < 0.15	0.50–0.85	all < 0.15	5.10–10.9	2.99–14.2	3,376–12,730	6.52–14.7	175–427	4.63–15.0	<0.24–0.79	4.02–15.8
43 (a–c)	mean	nc	0.40	nc	4.78	2.20	2,237	4.14	183	3.50	nc	3.10
	range	all < 0.15	0.37–0.43	all < 0.15	4.24–5.17	2.14–2.31	2,100–2,481	3.55–5.17	163–208	3.15–3.75	all < 0.26	3.03–3.22
44 (a–c)	mean	nc	0.50	nc	4.58	1.41	1162	2.01	107	2.75	0.39	2.61
	range	all < 0.15	0.38–0.65	all < 0.15	4.43–4.70	1.25–1.61	912–1,947	1.75–2.61	103–113	2.59–2.89	<0.24–0.50	2.21–3.38

nc = not calculable; no sediment found at sites 1, 2, 3 and 32.

[a] Mean = geometric mean.

[b] Mercury data expressed as ng/g dry wt.

The trace metal data for sediments are summarised in Table 4. Despite some significant variations within the bay some patterns are forthcoming. All the silver and cadmium concentrations were below analytical detection limits, indicating negligible impact from these elements in the bay. Many samples gave non-detectable lead values and a few yielded non-detectable concentrations of nickel. For other elements, all samples gave detectable results, some covering a wide range. Given that the sediments in this area come from two dominant sources (i.e., calcareous reef materials produced in the bay and volcanic soils from terrestrial sources), with very different elemental compositions, the metal distribution patterns can be explained. Most of the iron and related ferrous metals detected, like manganese, chromium, copper, nickel and zinc were associated with the volcanic materials that predominated in the southern half of the bay. The elemental composition of these deposits was similar to that encountered earlier in river sediments upstream of the landfill (Denton et al., 2007) implying negligible contributions from this facility. Levels also decreased on moving from the river mouth to the reef edge (sites 10 and 41–44) in keeping with a progressively increasing carbonate content of deposits in this general direction (reef carbonates typically contain low amounts of ferrous metals (Morse and McKenzie, 1990)). Finally, good correlations were found between iron and related elements with coefficients ranging from 0.74 (iron/copper) to 0.97 (iron/zinc). In contrast, poor correlations (0.16–0.49) were found between iron and the non ferrous metals, arsenic, mercury and lead. Similar relationships within and between calcareous and volcanic derived materials were found for Laucala Bay, Fiji (Morrison et al., 2001) and Fanga'uta Lagoon, Tonga (Morrison and Brown, 2003).

While no obvious concentration gradients for any element in the bay could be linked with the activities of the landfill, areas of mild enrichment attributable to other sources were identified for mercury, lead and zinc and are briefly discussed here.

Mean mercury concentrations found in Pago Bay sediments during the present study ranged from 1.55–13.6 ng/g with higher levels generally occurring in the alluvial deposits analyzed. The notable exception was at site 31, at the northern end of the bay, where 10.1–15.7 ng/g were detected in calcareous sediments down gradient of the University of Guam. Clean bioclastic deposits typically contain 1–2 ng/g (Denton et al., 1997, 2001). The higher levels at site 31 were attributed to leachate from septic tank wastewater disposal systems that service a limited number of buildings in the area.

Lead levels normally encountered in clean river sediments upstream from the Ordot landfill rarely exceed 1 μg/g and are similar to calcareous reef deposits in this regard (Denton et al., 2001, 2007). Sedimentary lead levels recorded during the present investigation ranged from <0.26 μg/g in predominantly bioclastic material to 14.4 μg/g in alluvial deposits at site 5 at the southern end of the bay near an old military rifle range. A localized area of light enrichment was also identified at the northern end of the bay at sites 30 and 31 and likely reflects contributions from septic tank leachate and stormwater runoff from the University of Guam campus.

Sedimentary zinc concentrations found in the present study, although highest in alluvial deposits around the river mouth, were no higher than levels found in bottom deposits in the Lonfit River upstream of the landfill (Denton et al., 2007). Some minor enrichment was noted at shoreline sites impacted by groundwater intrusion and urban runoff in the middle reaches of the bay (sediment site 23), and near the University of Guam further north (site 31).

Wide ranges of metal concentrations were also found within and between the biotic groups analysed (Tables 5–8). The data were interpreted by comparative assessments with similar and related species from clean and polluted environments elsewhere (Table 9). Of particular importance here was the information available for identical species collected from metal enriched sediments adjacent to a coastal dumpsite in the neighbouring island of Saipan, the largest island in the CNMI (Commonwealth of the Northern Mariana Islands) (Denton et al., 2008).

Biotic silver values were all either below or very close to analytical detection limits, in line with the low concentrations found in sediments, and confirming that this element is not an issue in Pago Bay. Arsenic concentrations mostly fell within the 2–60 μg/g range normally found for marine organisms (Eisler, 1981), although levels in *Sargassum* and *Turbinaria* were frequently much higher when expressed on a dry weight basis (Table 5). Nevertheless, the data confirmed that arsenic is not a problem element in Pago Bay. The absence of detectable cadmium concentrations in the great

Table 5
Trace metals (μg/g dry wt) in algae from Pago Bay, Guam

Species	Site	Date	Statistic[a]	Ag	As[b]	Cd	Cr	Cu	Fe	Hg[c]	Mn	Ni	Pb	Zn
Acanthopora spicifera	39	28-Jul-05	mean	nc	0.73	0.30	1.07	2.57	689	2.13	18.2	4.33	nc	3.32
			range	all < 0.15	0.39–1.11	0.3–0.3	0.80–1.57	2.42–2.71	588–801	1.72–2.37	15.5–21.6	3.97–5.20	all < 0.32	3.14–3.61
	41	28-Jul-05	mean	nc	1.31	0.30	1.21	2.69	754	1.72	13.3	3.81	nc	4.70
			range	all < 0.15	0.84–1.72	0.29–0.30	0.98–1.40	2.24–3.03	609–877	1.68–1.76	12.7–14.6	3.20–4.15	<0.3 0–0.62	4.33–5.00
	42	15-Aug-05	mean	nc	0.21	0.34	1.49	2.87	580	1.52	13.7	3.91	nc	7.35
			range	all < 0.15	0.20–0.22	0.30–0.47	1.03–1.88	2.77–3.15	516–679	1.17–1.74	12.6–14.3	3.82–4.03	<0.34–0.70	6.96–8.04
	46	5-Jul-05	mean	nc	0.61	nc	nc	1.55	314	1.29	7.01	3.35	nc	3.49
			range	all < 0.15	0.48–0.92	all < 0.18	all < 0.27	1.49–1.58	275–351	1.09–1.72	6.86–7.17	3.05–3.54	all < 0.41	3.36–3.83
	47	5-Jul-05	mean	nc	0.45	nc	nc	1.26	208	2.00	6.75	3.27	0.89	3.85
			range	all < 0.15	0.21–1.09	all < 0.27	all < 0.39	1.22–1.31	192–227	1.67–2.83	6.38–7.04	3.24–3.35	<0.42–1.36	3.88–4.08
Gracilaria salicornia	42	5-Jul-05	mean	nc	1.53	nc	0.76	0.61	104	2.55	15.0	0.29	nc	3.18
			range	all < 0.16	1.44–1.67	all < 0.16	0.58–1.15	0.47–0.72	83.4–145	2.35–2.99	13.8–17.5	<0.16–0.64	all < 0.35	2.92–3.60
	48	15-Aug-05	mean	nc	1.57	nc	0.41	1.06	38.5	2.40	7.89	0.52	nc	8.40
			range	all < 0. 26	1.43–1.67	all < 0. 26	<0.25–0.75	0.98–1.17	35.2–40.1	1.74–3.48	7.60–8.37	<0.22–1.07	all < 0.58	8.12–8.71
Caulerpa rasemosa	10	15-Aug-05	mean	nc	1.19	nc	0.44	0.98	436	1.18	10.3	1.40	nc	2.16
			range	all < 0.15	1.04–1.53	all < 0.15	0.41–0.60	0.77–1.19	345–527	1.17–1.20	8.89–11.7	1.19–1.55	<0.34–1.05	1.86–2.39
Caulerpa serrulata	44	5-Jul-05	mean	nc	1.82	nc	nc	0.83	470	3.14	12.1	1.92	nc	1.98
			range	all < 0.22	1.66–2.22	all < 0.22	all < 0.31	0.67–0.90	448–517	3.01–3.66	11.2–13.1	1.65–2.16	all < 0.48	1.73–2.12
Caulerpa sertalarioides	48	5-Jul-05	mean	nc	2.82	nc	0.50	1.41	65.5	3.94	14.5	1.58	nc	4.37
			range	all < 0.21	2.19–3.48	all < 0.21	<0.3–1.09	1.31–1.49	62.0–69.5	3.50–4.19	13.6–15.4	1.51–1.65	all < 0.46	4.13–4.52
Chlorodesm is fastigiata	21	19-Aug-05	mean	nc	9.55	nc	2.14	2.34	696	6.63	23.9	1.06	nc	4.61
			range	all < 0.15	9.24–9.90	all < 0.15	1.91–2.40	2.29–2.40	617–784	6.52–6.81	21.3–26.7	0.95–1.17	all < 0.34	4.51–4.72
Padina boryana	27	19-Aug-05	mean	nc	3.11	nc	1.45	3.00	1310	2 52	102	3.20	nc	3.12
			range	all < 0.15	2.86–3.33	all < 0.15	1.25–1.47	2.88–3.09	1208–1516	2.27–2.97	91.4–108	2.97–3.36	<0.31–0.63	3.07–3.20
	28	19-Aug-05	mean	nc	2.29	nc	2.03	4.26	1585	1.75	91.3	2.99	1.79	4.48
			range	all < 0.15	1.96–2.78	all < 0.15	1.86–2.14	4.13–4.65	1451–1828	1.70–1.78	88.4–94.9	2.70–3.30	1.58–1.88	4.37–4.65
	42	15-Aug-05	mean	nc	3.36	0.29	1.29	1.10	530	1.91	48.6	1.80	nc	3.84
			range	all < 0.16	2.95–3.60	0.23–0.32	0.94–1.68	0.87–1.26	440–590	1.74–2.29	42.1–52.4	1.56–2.15	0.27–0.66	3.65–4.16
	44	5-Jul-05	mean	nc	2.49	nc	nc	0.91	458	1.75	24.4	2.19	nc	2.28
			range	all < 0.16	2.34–2.69	all < 0.16	all < 0.23	0.82–1.06	403–501	1.72–1.81	22.2–27.0	2.03–2.39	all < 0.35	2.03–2.50
	45	5-Jul-05	mean	nc	3.16	nc	nc	1.01	437	1.82	23.2	2.05	nc	7.49
			range	all < 0.16	2.52–3.71	all < 0.16	all < 0.23	0.96–1.07	408–458	1.12–2.34	21.5–25.9	1.98–2.14	all < 0.35	6.14–8.27
	47	5-Jul-05	mean	nc	10.6	nc	nc	0.88	304	1.02	22.1	1.69	7.58	3.11
			range	all < 0.18	10.3–11.0	all < 0.18	all < 0.26	0.74–0.94	262–358	0.59–1.62	19.0–24.0	1.59–1.85	4.24–13.9	2.75–3.36
Sargassum cristafolium	1	16-Sep-05	mean	nc	39.3	0.21	nc	1.23	80.0	2.33	13.1	3.33	nc	2.41
			range	all < 0.10	36.0–45.6	0.20–0.29	<0.14–0.44	0.98–1.49	69.7–105	2.29–2.39	5.6–19.0	2.22–4.15	all < 0.19	2.06–2.58
	2	5-Jul-05	mean	nc	38.3	nc	nc	1.10	20.3	2.85	4.44	1.04	2.31	4.63
			range	all < 0.19	36.1–40.5	all < 0.19	all < 0.28	0.94–1.25	17.3–21.7	2.32–3.46	4.36–4.67	0.68–1.19	1.80–2.99	4.28–4.83
	3	5-Jul-05	mean	nc	13.5	nc	nc	0.78	68.7	2.54	5.11	1.24	2.28	3.02
			range	all < 0.17	12.0–15.8	all < 0.17	all < 0.25	0.73–0.84	59.3–76.8	2.31–2.99	4.86–5.43	0.99–1.39	1.69–2.99	2.85–3.21
	4	5-Jul-05	mean	nc	32.2	nc	nc	0.64	31.4	2.10	5.12	1.45	0.67	2.55
			range	all < 0.16	30.1–35.0	all < 0.16	all < 0.22	0.59–0.69	21.3–58.5	1.72–2.40	4.89–5.32	1.13–2.01	0.65–0.69	2.27–2.81
	5	5-Jul-05	mean	nc	36.7	nc	nc	0.92	63.2	2.71	4.68	2.44	0.59	2.25
			range	all < 0.16	32.3–39.9	all < 0.16	all < 0.23	0.77–1.09	48.2–79.9	2.41–2.99	3.71–5.69	2.01–2.88	<0.35–0.71	1.82–3.76
	6	5-Jul-05	mean	nc	57.1	nc	nc	0.71	40.7	3.78	2.84	2.47	2.72	1.37
			range	all < 0.16	53.5–61.9	all < 0.15	all < 0.23	0.59–0.82	35.8–45.8	3.40–4.06	2.61–3.07	2.33–2.75	1.96–5.22	1.17–1.62

(continued on next page)

Table 5 (*continued*)

Species	Site	Date	Statistic[a]	Ag	As[b]	Cd	Cr	Cu	Fe	Hg[c]	Mn	Ni	Pb	Zn
	7	5-Jul-05	mean	nc	41.9	nc	nc	0.74	50.8	3.44	3.36	2.94	0.52	1.07
			range	all < 0.16	40.8–44.2	all < 0.16	<0.21–0.44	0.58–0.86	30.4–65.3	3.42–3.46	3.09–3.63	2.81–3.14	<0.33–0.73	0.76–1.88
	8	5-Jul-05	mean	nc	61.9	nc	nc	0.58	41.2	2.81	3.12	2.75	nc	1.06
			range	all < 0.16	50.9–70.5	all < 0.16	all < 0.23	0.53–0.77	22.3–64.0	2.32–3.35	2.76–3.77	2.15–3.40	all < 0.36	0.76–1.35
	9	5-Jul-05	mean	nc	83.8	nc	nc	0.83	88.1	2.86	8.06	4.55	nc	1.01
			range	all < 0.16	70.9–97.3	all < 0.16	<0.21–0.42	0.78–0.88	66.7–142	2.39–3.40	3.29–16.9	3.36–6.29	<0.32–0.69	0.86–1.33
	10	15-Aug-05	mean	nc	23.6	nc	nc	0.73	103	2.14	7.27	1.66	nc	2.04
			range	all < 0.16	21.9–24.9	<0.15–0.31	all < 0.21	0.61–0.78	85.2–110	1.79–2.35	6.27–7.90	1.33–2.19	all < 0.35	1.83–2.24
	11	19-Jul-05	mean	nc	21.0	0.23	nc	0.95	109	1.75	7.53	3.07	nc	3.38
			range	all < 0.15	19.4–22.2	<0.15–0.30	all < 0.20	0.76–1.06	79.5–147	1.73–1.78	6.72–8.74	2.18–3.77	<0.30–0.63	2.84–3.88
	12	19-Jul-05	mean	nc	23.0	0.30	nc	1.01	131	1.90	11.1	4.25	nc	2.56
			range	all < 0.15	22.1–23.9	0.29–0.30	<0.19–0.39	0.91–1.05	122–147	1.73–2.27	10.0–13.7	3.94–4.80	all < 0.32	2.19–2.59
	13	19-Jul-05	mean	nc	16.9	0.30	nc	0.97	140	1.91	9.21	4.03	nc	2.44
			range	all < 0.16	13.5–20.1	0.29–0.31	<0.20–0.38	0.89–1.05	121–156	1.75–2.23	7.36–11.3	3.78–4.42	<0.30–0.63	2.20–2.66
	14	19-Jul-05	mean	nc	30.6	nc	nc	0.62	59.1	1.50	9.55	4.20	0.73	2.10
			range	all < 0.16	30.2–30.9	all < 0.16	all < 0.21	0.59–0.74	44.1–73.3	1.17–1.72	8.44–10.8	3.84–4.67	0.61–0.98	1.74–2.95
	15	19-Jul-05	mean	nc	24.0	nc	nc	0.51	56.2	1.52	6.02	2 32	nc	1.58
			range	all < 0.16	22.4–27.1	all < 0.16	all < 0.21	0.46–0.60	44.2–70.5	1.17–1.75	5.56–6.63	2.20–2.47	<0.31–0.62	1.49–1.70
	16	19-Jul-05	mean	nc	16.0	0.30	nc	0.80	154	1.48	8.02	2.60	nc	2.11
			range	all < 0.16	15.1–17.0	0.29–0.31	all < 0.20	0.74–1.07	97.7–250	1.12–1.71	7.48–8.12	2.18–3.15	<0.32–0.65	1.68–2.60
	17	19-Jul-05	mean	nc	26.5	nc	nc	1.00	267	2.61	20.7	6.37	0.37	1.84
			range	all < 0.16	20.9–30.5	all < 0.16	<0.20–0.41	0.79–1.22	184–307	2.21–2.86	16.9–27.8	5.07–8.00	<0.30–0.64	1.68–2.00
	18	19-Jul-05	mean	nc	48.1	nc	nc	1.38	418	2.43	8.32	3.47	nc	2.58
			range	all < 0.15	42.2–51.5	all < 0.15	<0.19–0.40	1.22–1.53	373–490	2.22–2.82	6.98–9.36	3.24–3.84	all < 0.32	2.32–2.76
	19	19-Aug-05	mean	nc	19.1	nc	0.85	1.39	534	1.55	17.2	2.48	nc	3.93
			range	all < 0.15	16.6–22.0	all < 0.15	0.60–1.20	1.20–1.63	470–653	1.20–1.77	15.0–18.7	2.15–2.67	all < 0.34	3.76–4.29
	20	19-Aug-05	mean	nc	57.8	nc	0.48	1.07	204	2.12	18.5	2.69	nc	3.14
			range	all < 0.16	50.6–72.7	all < 0.16	<0.20–0.83	0.91–1.25	154–281	1.76–2.34	12.8–28.3	2.37–2.79	all < 0.36	2.83–3.60
	21	19-Aug-05	mean	nc	112	0.26	nc	0.90	85.9	2.16	29.5	3.89	nc	2.56
			range	all < 0.16	108–117	<0.16–0.31	<0.20–0.39	0.78–1.09	71.8–97.8	1.80–2.39	24.0–36.7	3.66–4.49	all < 0.36	2.19–2.93
	22	19-Aug-05	mean	nc	44.6	nc	0.43	1.07	242	2.56	33.9	4.68	nc	2.30
			range	all < 0.15	37.8–49.9	all < 0.15	<0.21–0.79	0.92–1.33	136–508	2.38–2.93	27.7–40.7	4.38–5.13	all < 0.35	2.16–2.52
Sargassum polycystum	23	19-Aug-05	mean	nc	13.4	nc	1.06	1.69	854	1.91	89.7	3.16	nc	2.69
			range	all < 0.15	12.9–13.8	all < 0.15	0.93–1.29	1.60–1.82	787–1067	1.72–2.36	81.2–96.5	3.04–3.48	<0.30–0.63	2.56–2.88
	24	19-Aug-05	mean	nc	21.4	nc	1.82	2.38	1300	2.37	91.3	3.88	nc	3.54
			range	all < 0.16	20.4–22.4	<0.15–0.29	1.40–2.20	2.35–2.44	1196–1497	2.35–2.39	84.0–101	3.77–4.07	<0.30–1.51	3.36–3.85
	25	19-Aug-05	mean	nc	20.0	nc	2.00	2.67	1594	2.26	89.7	3.88	nc	4.26
			range	all < 0.16	19.1–21.4	all < 0.15	1.60–2.31	2.55–2.79	1341–1765	1.75–2.91	81.1–101	3.59–4.13	<0.31–1.48	4.06–4.36
	37	12-Aug-05	mean	nc	15.8	nc	0.74	1.01	285	2.11	33.9	1.62	nc	3.78
			range	all < 0.15	15.4–16.5	all < 0.15	0.60–0.96	0.92–1.05	236–347	1.73–2.33	29.4–42.0	1.48–1.77	all < 0.35	3.32–4.16
	39	28-Jul-05	mean	nc	19.4	nc	1.09	1.73	1000	2.65	60.2	3.84	nc	3.35
			range	all < 0.16	18.7–19.8	all < 0.16	0.82–1.63	1.55–2.10	816–1277	2.32–2.87	53.1–68.7	3.50–4.28	all < 0.33	3.09–3.60
	40	28-Jul-05	mean	nc	12.3	nc	2.07	2.40	1461	3.16	55.6	4.26	nc	5.08
			range	all < 0.16	10.7–13.8	all < 0.16	1.81–2.66	2.20–2.65	1330–1576	2.87–3.61	52.6–59.6	4.01–5.01	<0.31–0.64	4.54–7.01

	41	15-Aug-05	mean	nc	16.3	nc	2.18	2.50	1456	2.37	56.3	4.26	nc	4.07
			range	all < 0.16	14.2–18.0	all < 0.15	1.96–2.50	2.24–2.63	1254–1681	2.34–2.42	53.5–61.3	3.91–4.52	all < 0.31	3.73–4.32
	42	15-Aug-05	mean	nc	11.2	nc	1.00	1.06	442	1.77	40.7	1.81	nc	3.20
			range	all < 0.15	9.61–12.2	all < 0.16	0.79–1.26	1.03–1.10	405–499	1.73–1.82	37.1–42.9	1.80–1.90	all < 0.36	3.11–3.40
Turbinaria ornata	26	19-Aug-05	mean	nc	8.80	nc	0.44	1.03	333	2.34	6.97	1.31	nc	1.73
			range	all < 0.16	8.58–9.22	all < 0.16	<0.16–0.83	0.90–1.25	209–573	2.32–2.36	5.76–8.14	1.11–1.69	all < 0.32	1.51–2.14
	40	28-Jul-05	mean	nc	34.1	0.23	nc	0.88	348	4.82	9.37	1.47	nc	2.20
			range	all < 0.16	32.0–36.9	<0.15–0.30	all < 0.21	0.73–1.19	247–485	4.62–5.20	7.62–11.3	1.27–1.77	all < 0.33	1.68–2.83
	41	28-Jul-05	mean	nc	21.0	nc	1.14	1.51	921	2.11	15.3	2.59	nc	3.81
			range	all < 0.15	18.5–23.2	<0.15–0.29	0.96–1.38	3.58–4.37	731–1207	1.75–2.35	12.9–18.2	2.22–3.22	<0.31–0.61	3.58–4.37
	43	15-Aug-05	mean	nc	28.4	nc	0.43	0.66	260	4.11	6.54	1.24	nc	1.89
			range	all < 0.16	27.4–30.4	<0.14–0.30	0.38–0.63	0.60–0.79	178–419	4.07–4.16	5.43–8.36	0.84–1.58	all < 0.36	1.73–2.06
	44	5-Jul-05	mean	nc	18.3	nc	nc	0.35	144	3.45	4.16	0.66	nc	1.77
			range	all < 0.24	15.7–21.1	all < 0.24	all < 0.35	0.30–0.43	123–177	3.40–3.50	3.96–4.35	0.58–0.74	all < 0.53	1.62–1.91
	45	5-Jul-05	mean	nc	21.0	nc	nc	0.38	114	3.82	3.92	0.80	nc	2.51
			range	all < 0.16	18.5–22.8	all < 0.16	all < 0.24	0.34–0.43	106–134	3.35–4.13	3.74–4.23	0.75–0.90	all < 0.36	2.44–2.55
	47	5-Jul-05	mean	nc	22.2	nc	nc	0.46	55.3	2.86	2.96	0.61	nc	2.01
			range	all < 0.26	21.4–23.0	all < 0.26	all < 0.37	0.41–0.53	48.7–69.2	2.77–2.94	2.88–3.09	0.49–0.75	<0.45–1.62	1.80–2.21

[a] Mean as geometric mean ($n = 4–5$ replicates per site).

[b] Arsenic concentrations as µg/g wet weight.

[c] Mercury concentrations as ng/g wet weight; nc = not calculable.

majority of biota samples tested also indicates this element is not of current concern.

Despite marginally elevated copper levels in the sediments adjacent to the Ordot landfill (Denton et al., 2007), the concentrations determined in Pago Bay biota rank among the lowest values ever reported for similar and related species from elsewhere (Table 9). Those encountered in seaweeds (Table 5) and seagrass (Table 6) from the bay ranged from 0.30–4.65 µg/g and 0.74–5.73 µg/g, respectively, with the great majority of samples yielding values below 3 µg/g. Since levels in marine plants are normally <10 µg/g (Moore, 1991), these data indicate no copper contamination in the area. This was confirmed by the bivalve mollusc, *Q. palatum*, which gave concentrations of 4.36–68.9 µg/g here (Table 8) compared with 324–1027 µg/g in specimens from Saipan (Table 9).

Marine algae are effective accumulators of iron and concentrate it to levels several orders of magnitude above ambient. Values reported in the literature range from <10 µg/g to >10,000 µg/g (Eisler, 1981). Levels found in the present study were relatively low by comparison, ranging from ∼20–1,800 µg/g, with (as might be expected) the highest values levels occurring in specimens closest to the river channel and shoreline sites impacted by groundwater intrusion. Seagrass concentrations were similarly low when compared with related species from tropical waters elsewhere in the world. No comparative iron data were found for seacucumber tissues, although two independent studies conducted whole body analyses of *Holothuria* spp., and reported values ranging from 74–200 µg/g in specimens from the Sea of Japan (Matsumoto et al., 1964) and the Mediterranean (Papadopoulu et al., 1976). These values are generally higher than those found in *H. atra* during the present study (Table 7). The bivalves examined here likely exercise some metabolic control over their iron uptake (since all have haemoglobin as their respiratory blood pigment) and are, therefore, unsuitable for monitoring the distribution and abundance of this element in the marine environment. This notwithstanding, the overall message from the biotic components examined suggests only moderate to low levels of available iron in the Pago Bay area.

In 1993, the USEPA, declared mercury an element of potential concern in the Lonfit River based largely on erroneously high sediment data reported in the early 1980s (Black and Veatch, 1983). More recent studies have failed to detect mercury in the Lonfit River, or in leachate draining into it (Denton et al., 2005 b). Likewise, Lonfit River sediments were found to be relatively free of mercury contamination with only mild enrichment occurring around points of confluence with the leachate streams (Denton et al., 2007). The absence of any significant mercury build-up in the watershed was also reflected in sediment and organism data from the bay during the current study. For example, the mean mercury concentrations found in algae and seagrass from within Pago Bay ranged from 1.02 to 6.6 ng/g wet weight and rank among the lowest values ever recorded (Table 9). For the seacucumber, *H. atra*, values of up to 52.3 ng/g wet weight were found in the hemal system, well below the upper concentration of 400 ng/g wet weight suggested by Eisler (1981) for echinoderms from non-polluted environments. Bivalve molluscs are excellent indicators of mercury and tissue concentrations in representatives from clean environments rarely exceed 100 ng/g wet weight. Levels found in specimens during the current study ranged from 5.63 to 62.4 ng/g wet weight, providing further evidence that Pago Bay does not have a mercury contamination problem.

Manganese data in both algae and seagrass were lower than those reported in the literature for related species from elsewhere. Similarly, seacucumbers analyzed during the current work yielded values that were considerably lower than those normally found in other types of echinoderms (∼40 µg/g, Bryan, 1976). Manganese concentrations in bivalves analyzed during the current study, ran-

Table 6
Trace metals (µg/g dry wt.) in the seagrass *Enhalus acoroides* from Pago Bay, Guam

Site	Date	Statistic[a]	Ag	As[b]	Cd	Cr	Cu	Fe	Hg[c]	Mn	Ni	Pb	Zn
29	29-Aug-05	mean	nc	0.25	nc	nc	2.92	115	1.83	12.4	1.85	nc	12.9
		range	all < 0.15	0.20–0.28	all < 0.15	<0.16–0.16	2.75–3.22	97.4–147	1.82–1.85	10.7–14.1	1.26–2.39	all < 0.31	32.0–1.69
30	29-Aug-05	mean	nc	0.14	nc	0.35	4.76	139	1.80	15.3	1.96	nc	15.5
		range	all < 0.16	0.10–0.17	all < 0.15	<0.16–0.64	4.39–5.19	113–165	1.79–1.82	14.0–17.5	1.50–2.28	all < 0.32	13.4–16.6
31	29-Aug-05	mean	nc	0.12	nc	0.41	5.18	224	3.19	32.3	3.36	nc	9.56
		range	all < 0.16	0.10–0.20	all < 0.16	0.32–0.49	4.83–5.73	189–273	3.00–3.56	30.1–36.4	2.61–4.26	all < 0.32	8.52–10.2
32	30-Aug-05	mean	nc	0.16	nc	0.28	2.40	108	2.00	13.0	2.13	nc	11.1
		range	all < 0.15	0.10–0.20	all < 0.15	<0.15–0.48	2.32–2.58	81.5–130	1.78–2.43	11.4–14.3	1.39–2.93	all < 0.31	9.42–12.8
33	12-Aug-05	mean	nc	0.23	nc	nc	1.84	138	1.78	11.7	1.87	0.74	8.78
		range	all < 0.16	0.22–0.24	all < 0.16	all < 0.21	1.66–1.95	128–162	1.75–1.84	11.2–12.0	1.67–2.15	0.68–1.02	8.62–8.94
34	12-Aug-05	mean	nc	0.32	nc	0.27	1.45	89.3	1.54	8.35	1.91	nc	8.16
		range	all < 0.16	0.21–0.42	all < 0.16	<0.20–0.42	1.32–1.56	69.2–120	1.20–1.81	8.06–8.72	1.79–2.19	all < 0.35	7.43–9.03
35	12-Aug-05	mean	nc	0.20	nc	nc	1.65	78.3	1.33	8.30	1.90	nc	7.88
		range	all < 0.16	0.20–0.21	all < 0.16	all < 0.21	1.38–1.79	68.0–102	1.14–1.81	7.78–8.89	1.66–2.21	<0.34–0.70	7.17–9.03
36	12-Aug-05	mean	nc	0.26	nc	nc	1.45	69.4	1.51	8.20	1.95	nc	8.76
		range	all < 0.16	0.20–0.41	all < 0.16	all < 0.21	1.41–1.57	61.7–83.1	1.16–1.72	7.99–8.50	1.57–2.73	<0.34–0.71	6.81–10.0
37	12-Aug-05	mean	nc	0.50	nc	nc	1.40	81.7	1.69	8.69	2.76	0.81	7.41
		range	all < 0.16	0.21–0.90	all < 0.16	<0.20–0.63	1.33–1.57	75.6–90.0	1.21–2.31	8.10–9.10	2.44–2.95	0.67–1.07	6.78–7.84
38	28-Jul-05	mean	nc	0.78	nc	nc	0.85	111	1.36	10.9	2.87	nc	5.25
		range	all < 0.16	0.51–1.04	all < 0.16	all < 0.21	0.74–0.92	87.7–167	1.14–1.79	10.4–11.5	2.69–3.30	all < 0.32	4.96–5.50
41	28-Jul-05	mean	nc	0.75	nc	nc	1.21	88.1	1.52	7.15	2.18	0.53	6.40
		range	all < 0.16	0.59–1.22	all < 0.16	all < 0.91	0 98–1 40	59 1–109	1.13–1 77	4.61–8.10	1 37–2.77	<0 30–0 95	5 91–7 02

nc = not calculable.

[a] Mean as geometric mean (*n* = 5 replicates per site).

[b] Arsenic concentrations as µg/g wet weight.

[c] Mercury concentrations as ng/g wet weight.

Table 7
Trace metals (µg/g dry wt) in the seacucumber *Holothuria atra* from Pago Bay, Guam

Site	Date	Tissues[a]	Statistic[b]	Ag	As[c]	Cd	Cr	Cu	Fe	Hg[d]	Mn	Ni	Pb	Zn
4	17-Aug-05	*M*	mean	<0.09	3.06	<0.09	0.30	1.23	19.7	2.01	0.28	<0.09	<0.19	14.3
			range	–	3.02–3.13	–	–	–	–	1.75–2.48	–	–	–	–
4	17-Aug-05	*H*	mean	<0.63	10.5	<0.63	0.67	5.69	80.9	17.9	1.90	1.16	<1.29	56.9
			range	–	9.54–11.2	–	–	–	–	16.1–20.0	–	–	–	–
6	17-Aug-05	*M*	mean	<0.10	3.82	<0.10	0.21	1.01	22.8	1.90	0.40	0.19	<0.21	13.5
			range	–	3.76–3.90	–	–	–	–	1.73–2.25	–	–	–	–
6	17-Aug-05	*H*	mean	<0.54	6.39	0.54	1.14	3.76	65.0	15.0	1.07	<0.49	<1.10	66.6
			range	–	6.00–7.08	–	–	–	–	14.5–15.5	–	–	–	–
12	17-Aug-05	*M*	mean	<0.09	2.84	<0.09	0.18	1.08	26.8	1.93	0.43	0.16	<0.18	13.1
			range	–	2.54–3.10	–	–	–	–	1.77–2.28	–	–	–	–
12	17-Aug-05	*H*	mean	<0.19	4.78	<0.19	1.80	6.14	54.4	12.8	2.82	0.34	<0.38	67.5
			range	–	4.48–5.26	–	–	–	–	11.1–14.4	–	–	–	–
13	17-Aug-05	*M*	mean	<0.09	5.35	<0.09	<0.10	1.62	30.8	2.30	0.82	0.17	<0.18	16.2
			range	–	4.80–5.83	–	–	–	–	1.78–2.82	–	–	–	–
13	17-Aug-05	*H*	mean	<0.53	1.42	<0.53	13.6	6.27	292	3.55	3.19	0.97	<1.08	301
			range	–	1.29–1.56	–	–	–	–	3.16–4.00	–	–	–	–
16	17-Aug-05	*M*	mean	<0.10	2.98	<0.10	0.32	1.04	19.1	1.54	0.40	0.27	<0.20	12.8
			range	–	2.67–3.35	–	–	–	–	1.13–1.85	–	–	–	–
16	17-Aug-05	*H*	mean	<0.20	4.09	<0.20	3.85	6.27	84.4	17.4	1.00	0.37	<0.41	74.5
			range	–	3.78–4.39	–	–	–	–	9.35–45.3	–	–	–	–
17	18-Aug-05	*M*	mean	<0.09	2.49	<0.09	<0.09	0.89	39.5	1.77	0.61	0.24	<0.18	13.3
			range	–	2.41–2.64	–	–	–	–	1.65–1.87	–	–	–	–
17	18-Aug-05	*H*	mean	<0.27	–	<0.27	4.24	3.82	144	–	1.59	0.49	<0.54	125
			range	–	–	–	–	–	–	–	–	–	–	–
19	18-Aug-05	*M*	mean	<0.14	1.96	<0.14	<0.14	1.40	17.5	1.78	0.54	<0.12	<0.28	17.8
			range	–	1.77–2.13	–	–	–	–	1.74–1.84	–	–	–	–
19	18-Aug-05	*H*	mean	<0.77	4.27	<0.77	4.08	5.05	81.3	11.2	3.07	<0.70	<1.57	157
			range	–	4.24–4.30	–	–	–	–	9.32–13.3	–	–	–	–
20	18-Aug-05	*M*	mean	<0.13	4.37	<0.13	0.29	1.30	20.5	2.62	0.54	0.37	<0.28	15.5
			range	–	3.98–4.95	–	–	–	–	2.37–3.07	–	–	–	–
20	18-Aug-05	*H*	mean	<0.63	6.72	<0.63	2.00	3.75	63.9	45.1	1.88	<0.58	<1.28	80.7
			range	–	6.61–6.91	–	–	–	–	35.8–52.3	–	–	–	–
22	18-Aug-05	*M*	mean	<0.13	4.88	<0.13	0.28	1.54	21.9	2.65	0.78	<0.12	<0.26	16.7
			range	–	4.32–5.61	–	–	–	–	1.71–4.48	–	–	–	–
22	18-Aug-05	*H*	mean	<0.78	4.85	<0.78	5.00	6.37	91.7	31.7	3.92	<0.72	<1.60	154
			range		4.69–5.02	–	–	–	–	24.2–41. 4	–	–	–	–

[a] Tissues: *M* = body wall, *H* = hemal system.

[b] Mean as geometric mean (n = 3–5 replicate samples per site for arsenic and mercury and one for all other metals).

[c] Arsenic concentrations as µg/g wet weight.

[d] Mercury concentrations as ng/g wet weight; dashes indicate no data.

Table 8
Trace metals (μg/g dry wt.) in bivalves from Pago Bay, Guam

Species	Site	Date	Statistic[a]	Ag	As[b]	Cd	Cr	Cu	Fe	Hg[c]	Mn	Ni	Pb	Zn
Asaphia violascens	48	23-Jun-05	mean	0.11	–	0.11	0.16	7.61	971	–	15.2	5.87	0.81	72.9
			range	–	–	–	–	–	–	–	–	–	–	–
Ctena bella	31	29-Aug-05	mean	0.09	–	0.66	0.14	20.9	74.0	–	3.03	7.83	0.54	205
			range	–	–	–	–	–	–	–	–	–	–	–
	34	13-Aug-05	mean	nc	4.68	1.55	nc	6.24	68.5	11.6	2.18	14.6	0.55	191
			range	all < 0.13	4.61–4.74	1.29–1.86	all < 0.20	5.84–6.67	63.2–74.3	11.5–11.8	2.00–2.39	10.1–21.2	<0.20–100	126–289
	36	30-Aug-05	mean	nc	4.59	1.60	nc	7.7	62.9	5.63	1.88	14.6	0.72	167
			range	all < 0.18	–	1.02–2.51	all < 0.27	7.54–7.96	55.1–71.8	–	1.63–2.15	10.7–19.8	0.39–1.35	112–248
	37	23-Jun-05	mean	0.12	6.89	0.72	0.18	5.79	65.1	17.4	2.53	9.75	0.45	164
			range	–	–	–	–	–	–	–	–	–	–	–
Gafrarium pectinatum	34	13-Aug-05	mean	0.14	–	1.14	0.21	17.0	386	–	22.9	16.4	0.27	59.6
			range	–	–	–	–	–	–	–	–	–	–	–
Quidnipagus palatum	29	29-Aug-05	mean	nc	20.5	nc	0.25	30.1	791	32.7	4.46	12.4	0.62	188
			range	all < 0.09	15.3–27.2	all < 0.10	<0.13–0.46	24.6–36.9	726–862	25.8–38.3	3.49–5.72	12.1–12.6	0.50–0.77	157–226
	31	29-Aug-05	mean	0.13	19.7	nc	0.19	66.8	1253	58.4	20.8	24.1	0.65	279
			range	<0.13–0.13	19.6–19.8	all < 0.30	<0.19–0.20	65.1–68.5	1214–1292	54.6–62.4	18.6–23.1	23.5–24.7	0.47–0.89	268–290
	36	30-Aug-05	mean	0.10	–	0.10	0.16	6.03	601	–	5.10	10.4	<0.20	93.6
			range	–	–	–	–	–	–	–	–	–	–	–
	48	23-Jun-05	mean	nc	11.3	nc	nc	4.52	724	26.2	3.95	15.7	0.29	323
			range	all < 0.08	9.71–14.0	all < 0.08	all < 0.20	4.26–4.80	677–775	21.9–25.0	2.92–5.34	15.4–16.0	0.29–0.30	306–341
Scutarcopajia scobinata	36	30-Aug-05	mean	0.34	–	0.34	1.01	6.07	2178	–	6.07	9.09	0.64	50.6
			range	–	–	–	–	–	–	–	–	–	–	–

nc = not calculable; dashes indicate no data.

[a] Mean as geometric mean (n = 1–3 replicates per site).

[b] Arsenic concentrations as μg/g wet weight.

[c] Mercury concentrations as ng/g wet weight.

ged from 1.63-23.9 μg/g, all below the average value of 25 μg/g given by Bryan (1976) for bivalves generally.

Nickel concentrations in algae from Pago Bay were not unusual and compare well with levels found in clean environments elsewhere (Denton and Burdon-Jones, 1986). They also support the earlier conclusion that sedimentary nickel concentrations in the bay were perfectly normal. The highest mean value in algae was 6.37 μg/g recorded in *S. cristafolium* from biota site 17 on the outer reef flat (Fig. 2), although the great majority of specimens from this group yielded values below 3 μg/g. Nickel levels in the bivalves examined were similarly low although a data comparison with their Saipan counterparts suggested they exhibit some degree of metabolic control over this element (Table 9). Likewise, the seacumber *H. atra* appears to limit its tissue concentrations to no more than 1–2 μg/g regardless of ambient nickel concentrations.

Lead concentrations in biota analyzed from Pago Bay generally mirrored the distribution profiles identified in the sediments. In algae, for example, the highest lead concentrations in *S. cristafolium* from the outer reef flat were found in specimens from biota sites 2–7 at the northern end of the bay. Relatively high lead contents were also seen in *P. boryana* from the inner moat area in this region (biota site 47) as well as in samples from the marginally lead enriched zone at the southern end of the bay (biota site 28). Algae, unlike seagrass, have a high affinity for lead and levels exceeding 100 μg/g have been reported in tropical species from relatively contaminated waters (Burdon-Jones et al., 1975; Agadi et al., 1978). Thus, the highest values reported here (maximum 13.9 μg/g) are no cause for concern.

The available literature strongly suggests that echinoderms are unable to regulate lead in their tissues. For example, Stennar and Nickless (1974) reported levels as high as 460 μg/g in various representatives from Norway, while Matsumoto et al. (1964) gave values of up to 14.4 μg/g wet weight in *Holothuria* sp. from lead-contaminated coastal waters of Japan. In contrast, lead levels were undetectable (<1.0 μg/g) in the body wall of *Stichopus variagatus* from pristine waters of the Great Barrier Reef (Burdon-Jones and Denton, 1984). Similarly low concentrations reflective of a clean environment were found in seacucumbers from Pago Bay during the present study.

Lead concentrations in the bivalve, *Q. palatum*, were marginally higher in specimens from seagrass beds at the southern end of Pago Bay compared with specimens collected north of the river. This species appears to be particularly sensitive to lead and concentrations approaching 200 μg/g have been recorded in contaminated samples from Saipan (Denton et al., 2008). Values recorded during the present study (<0.2–0.62 μg/g), therefore, were indicative of a comparatively clean coastal habitat by local standards.

Despite minor zinc enrichment of shoreline sediments in the middle reaches and northern part of Pago Bay, all biotic components examined contained relatively low levels of this element. Values in algae, for example, were all below 10 μg/g in keeping with levels normally encountered in specimens from clean environments (Denton and Burdon-Jones, 1986). Mean zinc concentrations in seagrass ranged from 5.25–15.5 μg/g and were appreciably lower than those found in *E. acoroides* from contaminated waters in Saipan (Denton et al., 2008). Although seagrass is not as sensitive to changes in ambient zinc availability as algae, the group does possess some bioindicator capability for this element (Denton et al., 2008). Concentrations found during the present investigation generally mirrored the sediment distribution pattern for this element with highest levels in specimens growing close to the Pago River mouth and along the southern shoreline. No such relationship was observed with the seacucumbers analysed. In fact, levels

Table 9
Trace metals (µg/g dry wt.) in marine biota from Pacific locations

Species	Location	Ag	As[a]	Cd	Cr	Cu	Fe	Hg[b]	Mn	Ni	Pb	Zn	References
Algae													
Acanthophora spicifera	Pago Bay, Guam	all < 0.27	0.20–1.55	0.16–0.47	<0.21–1.88	1.22–3.03	192–877	1.09–2.83	6.38–21.6	3.05–5.20	0.31–1.36	3.36–8.04	This study
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	Denton et al., 2008
Gracilaria salicornia	Pago Bay, Guam	all < 0.26	1.43–1.67	all < 0.26	<0..25–1.15	0.98–1.17	35.2–145	1.74–3.48	7.60–17.5	<0.16–1.07	all < 0.58	2.92–8.71	This study
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	Denton et al., 2008
Gracilaria sp.	N. Queensland coastal wateres, Australia	all < 0.2	–	<0.2–0.8	1.7–4.0	2.3–3.9	1250–2030		51.1–94.7	0.3–1.4	all < 0.4	11.2–15.6	Burdon–Jones et al., 1975
Caulerpa racemosa	Pago Bay, Guam	all < 0.15	1.04–1.53	all < 0.15	0.41–0.60	0.77–1.19	345–527	1.17–1.20	8.89–11.7	1.19–1.55	<0.34–1.05	1.86–2.39	This study
Caulerpa racemosa	Gt. Barrier Reef, Australia	–	–	0.17–0.48	–	1.4–2.6	–	22–246	–	0.82–1.6	<0.67–2.4	0.27–10.0	Denton and Burdon–Jones, 1986
Caulerpa serrulata	Pago Bay, Guam	all < 0.22	1.66–2.22	all < 0.22	all < 0.31	0.67–0.90	448–517	3.01–3.66	11.2–13.1	1.65–2.16	all < 0.48	1.73–2.12	This study
Caulerpa serrulata	Gt. Barrier Reef, Australia	–	–	0.20–0.49	–	1.0–2.4	–	–	–	0.78–2.4	all < 0.93	1.7–5.2	Denton and Burdon–Jones, 1986
Chlorodesmis fastigiata	Pago Bay, Guam	all < 0.15	9.24–9.90	all < 0.15	1.91–2.40	2.29–2.40	617–784	6.52–6.81	21.3–26.7	0.95–1.1	all < 0.34	4.51–4.72	This study
Chlorodesmis fastigiata	Gt. Barrier Reef, Australia	–	–	0.10–0.50	–	1.4–2.4	–	38–130	–	0.41–1.7	<0.57–2.1	1.3–12.1	Denton and 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 and Burdon–Jones, 1986
Padina boryana	Pago Bay, Guam	all < 0.18	1.96–11.0	<0.15–0.32	<0.23–2.14	0.74–4.65	262–1516	0.59–2.97	19.0–108	1.56–3.36	0.27–13.9	2.75–8.27	This study
Padina tenuis	Townsville coastal waters, Australia	<0.1–0.4	–	0.2–1.4	1.4–10.0	1.4–5.1	355–4037		37.8–496	0.7–8.4	<0.3–6.2	3.7–30	Burdon-Jones et al., 1982
Padina tetrostromatica	Townsville coastal waters, Australia	<0.1–0.4	–	0.2–1.2	1.6–9.9	2.0–11.1	606–8055		61.8–554	0.9–4.0	1.1–4.9	5.5–25.7	Burdon-Jones et al., 1982
Padina sp.	Gt. Barrier Reef, Australia	–	–	0.2	–	2.2	–	2	–	1.1	<0.74	5.9	Denton and Burdon-Jones, 1986
Padina sp.	Agana Boat Basin, Guam	0.89	32.2[c]	0.3	0.68	1.53	–	<2	–	1.18	0.46	11	Denton et al., 1999, 2006
Padina sp.	Apra Harbor, Guam	all < 0.10	5.8–38.1[c]	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, 2006
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	Denton et al., 2008
Sargassum cristafolium	Pago Bay, Guam	all < 0.16	2.39–117	<0.15–0.31	<0.20–1.20	0.46–1.63	17.3–653	1.12–4.06	2.61–40.7	0.68–5.13	<0.19–2.99	0.76–4.83	This study
Sargassum fulvellum	Korean waters	–	–	2.4–3.0	–	8–19	–	–	–	–	4.2–6.2	11–23	Pak et al., 1977
Sargassum horneri	Korean waters	–	–	1.7–2.7	–	9–25	–	–	–	–	6.7–8.9	28–61	Pak et al., 1977
Sargassum pallidum	VostokBay, Sea of Japan	–	–	–	–	4.3	–	–	–	–	–	2 7	Saenko et al., 1976
Sargassum polycystum	Pago Bay, Guam	all < 0.16	9.61–22.4	<0.15–0.29	0.60–2.66	0.92–2.79	236–1765	1.72–3.61	52.6–101	1.48–5.01	<0.31–1.51	2.56–7.01	This study
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	Denton et al., 2008

Sargassum sp.	N. Queensland coastal wateres, Australia	all < 0.2	–	all < 0.2	<0.4–3.1	2.2–3.1	1186–1398		29.7–48.8	<0.3–1.1	all < 0.4	7.0–10.0	Burdon-Jones et al., 1975
Seagrasses													
Enhalus acoroides	Pago Bay, Guam	all < 0.16	0.10–1.22	all < 0.16	<0.15–0.64	0.74–5.73	59.1–273	1.13–3.56	4.61–36.4	1.26–4.26	<0.30–1.07	4.96–16.6	This study
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	Denton et al., 2008
Halodule uninervis	Tanapag Lagoon, Saipan	all < 0.20	–	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	Denton et al., 2008
Halophila ovalis	Lockhardt River, Cape York, Australia	<0.2	–	0.5	1.0	9.0	4418		68.0	1.7	1	67.0	Denton et al., 1980
Zostera capricornia	Shoalwater Bay, N. Queensland, Australia	<0.2	–	0.2	1.9	2.8	3500		44.0	1.8	0.4	14.0	Denton et al., 1980
Seacucumbers[d]													
Holothuria atra (*M*)	Pago Bay, Guam	all < 0.14	1.77–5.83	all < 0.14	<0.09–0.30	0.89–1.62	17.5–39.5	1.13–4.48	0.28–0.82	<0.09–0.27	all < 0.28	12.8–17.8	This study
Holothuria atra (*H*)	Pago Bay, Guam	all < 0.78	1.29–11.2	all < 0.78	0.67–13.6	3.75–6.37	54.4–144	3.16–52.3	1.07–3.19	<0.49–1.16	all < 1.57	56.9–301	This study
Holothuria atra (*M*)	Apra Harbor, Guam	all < 0.12	13.6–23.2[c]	0.1–0.1	0.1–0.3	0.7–1.2	–	7–8	–	<0.2	all < 0.3	15.5–17.9	Denton etal., 1999, 2006
Holothuria atra (*H*)	Apra Harbor, Guam	<0.35–4.90	7.24–28.3[c]	0.25–0.26	2.21–8.58	4.70–5.19	–	49–88	–	all < 0.50	all < 0.92	120–180	Denton etal., 1999, 2006
Holothuria atra (*M*)	Small boat marinas, Guam	<0.12–0.24	all < 0.01[c]	0.1–0.1	all < 0.20	1.3–2.5	–	8–22	–	all < 0.20	all < 0.60	12.6–21.2	Denton etal., 1999, 2006
Holothuria atra (*H*)	Small boat marinas, Guam	<0.11–0.72	<0.01–0.18[c]	0.09–0.12	0.08–3.14	3.69–6.37	–	16–91	–	all < 0.43	all < 0.72	117–253	Denton etal., 1999, 2006
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	Denton et al., 2008
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	<0.1 1–6.33	29.8–287	Denton et al., 2008
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 and Denton, 1984
Bivalves							–		–				
Asaphia violascens	Pago Bay, Guam	0.11	–	0.11	0.16	7.61	971	–	15.2	5.87	0.81	72.9	This study
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	Denton et al., 2008
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	55.1–74.3	5.63–17.4	1.63–3.03	7.83–21.2	<0.20–1.35	112–289	This study
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	Denton et al., 2008
Gafrarium pectnatum	Pago Bay, Guam	0.14	–	1.14	0.21	17.0	386	–	22.9	16.4	0.27	59.6	This study
Gafrarium pectnatum	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	Denton et al., 2008
Gafrarium tumidum	Townsville coastal waters, Australia	5.3–5.7	–	0.3–0.3	0.6–1.6	7.1–7.7	787–1066		11.9–14.5	64.5–145	3.1–5.1	26.3–68.8	Burdon-Jones et al., 1975
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	601–1292	21.9–62.4	2.92–23.1	10.4–24.7	0.20–0.89	93.6–341	This study
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	Denton et al., 2008

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[a] Arsenic concentrations as μg/g wet weight.

[b] Mercury concentrations as ng/g wet weight.

[c] Arsenic concentrations as μg/g dry weight.

[d] Tissues: *M* = body wall, *H* = hemal system; dashes indicate no data.

in all specimens were remarkably close to the range of values found in representatives from Saipan, which strongly suggests these organisms exert some metabolic control for zinc. The bivalve, *G. pectinatum*, demonstrates a similar capability whereas its relative, *Q. palatum* clearly does not. Zinc concentrations in the latter species from Pago Bay ranged from 93.6–341 μg/g (mean 222 μg/g) compared with 305-1,027 μg/g (mean: 622 μg/g) in specimens from Saipan (Table 9).

In summary, this study shows that metal concentrations in the biotic and abiotic components of Pago Bay are generally low by world standards and largely reflect natural contributions associated with the alluvial discharges from the Pago River (volcanic detrital material), and groundwater intrusion. Localized areas of light enrichment occur for lead, mercury and zinc in shoreline sediments at the northern end of the bay and are probably associated with stormwater runoff from the University of Guam campus and the types of wastewater disposal systems currently in place there. A highly localized area of moderate lead enrichment occurs at the southern end of the bay near the site of an old abandoned military rifle range. Metal levels in biotic representatives from these sites, though marginally elevated in some species, remained well within the ranges typical of relatively clean environments.

The survey clearly demonstrates that Pago Bay is not a permanent sink for sediment bound metal contaminants mobilised from the Ordot landfill. This leads to the conclusion that any contaminated sediments deposited in and around the river mouth, the reef channel and the southern half of the bay during a normal wet season, are re-suspended and flushed from the system by major storms (typhoons) that approach the eastern side of the island. Under such conditions, the reef channel serves as a conduit for their transportation and dispersion into deeper waters offshore, beyond the reef margin. Thus, despite 60 years of continuous discharge of metal enriched leachate from the Ordot landfill into the Lonfit River, the climatic and topographic characteristics of the area combine to provide an effective means of periodically flushing out pockets of contaminated sediments from the entire watershed into the ocean. This rather unique situation has preserved the chemical integrity of fisheries resources in the area and removed a potential human health hazard that might otherwise have arisen.

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