Progress in Environmental Science and Technology, Vol. 1, (2007) 1169-1176. Science Press USA Inc.

Solid Waste Disposal on Guam: The Impact of an Unsanitary Landfill on the Heavy Metal Status of Adjacent Aquatic Community Representatives

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Abstract: Guam's only civilian landfill is located in the Lonfit River valley in the central part of the island. The landfill is unlined and continually discharges leachate into the adjacent watershed. The leachate is heavy metal enriched and its impact on the edible quality of aquatic resources in the area has been of long-standing concern to local residents. However, chemical analysis of abiotic and biotic components within the watershed failed to find any evidence of metal enrichment. Rather the data suggested that climatic and topographic conditions continually conspire to produce natural cleansing processes that prevent metal accumulation in the area.

Keywords: Guam, solid waste, unsanitary landfill, heavy metals, sediments, aquatic biota

1 Introduction

The only civilian landfill in Guam is located just outside the village of Ordot in the central part of the island (Figure 1 inset). The landfill been in continuous use for over 60 years and has been operating at over capacity for at least 20 years[1]. It currently occupies an area of ~60 acres and towers to ~90m at its mid-point[2]. The western border of the landfill encroaches onto wetlands that drain into the Lonfit River. This rather picturesque stream converges with the Sigua River further down current to form the Pago River, which in turn drains into Pago Bay, a fringing reef flat, on the eastern side of the island (Figure 1). Local residents fish all three rivers and the bay for food, and the adjacent lands support a variety of agricultural activities including subsistence farming.

Unlike modern sanitary landfills, the Ordot landfill is not lined with an impervious material and does not have a leachate retention system in place. As a consequence, streams of brown, foul smelling leachate continually flow from the facility's perimeter and course their way down gradient into the Lonfit River valley below. Past chemical characterization of the leachate indicates that heavy metals are the contaminants of primary concern both from an ecological and human health perspective[3]. This fact has promoted speculation that fisheries resources from these waters are heavy metal enriched to the point of being unfit for human consumption.

The heavy metal enrichment of leachate emanating from the Ordot landfill was recently confirmed by us[4]. Elements of primary concern included arsenic, chromium, copper, iron, lead, manganese, nickel and zinc. These elements were found to be present largely in particulate form and were presumed to be associated with insoluble oxides of iron and manganese formed upon leachate emergence from the landfill. While this natural precipitation process rapidly attenuates the soluble metal load moving downstream into the watershed, it adds significantly to the metal load of bed sediments in the leachate streams themselves. Mobilization rates of contaminated sediments from the leachate streams down into the Lonfit River and out into Pago Bay are currently unknown. Likewise, the impact of these deposits on aquatic organisms downstream of the landfill remains to be investigated. The following investigation addresses both of these deficiencies in our current level of understanding.

2 Materials and Methods

Surface sediments were collected in 100 ml acid-cleaned, polyethylene vials from 14 sites within the Lonfit-Sigua-Pago river system, and from 40 sites within Pago Bay (Fig. 1). River sampling sites extended from ~500 m upstream of the landfill in the Lonfit River to the Pago River mouth. Included in the sampling plan were bed sediments from two leachate streams emanating from the southwestern edge and southern toe of the landfill. Samples were taken from two sites on the former stream, the first approximately 100 m down gradient of the landfill and the second at the stream's point of confluence with the Lonfit River. The latter stream was sampled only at its confluence point (see Figure 1). Between 5-10 sediment samples were analyzed from each freshwater site within the watershed. In Pago Bay itself, triplicate sediment samples were collected at ~100 intervals along the beach and at ~100-m to 200-m along five equally spaced transect lines running perpendicular to the shore.

Biotic representatives in the rivers and bay exhibited patchy distributions and were collected on an opportunistic basis. Species selected for heavy metal analysis include those harvested for food (fish, crustaceans, mollusks, seacucumbers) by the local inhabitants in addition to those with known or potential bioindicator capability (aquatic plants, algae, mollusks).

In the laboratory, all sediment 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. Biotic samples were cleaned of residual sediments prior to drying at 60^{o}C. Those required for mercury analysis were analyzed wet to minimize losses by volatilization. All samples were analyzed for heavy metals by atomic absorption spectroscopy (AAS) following conventional wet oxidation in hot mineral acids. Full analytical details including QA/QC measures adopted are given elsewhere[5].

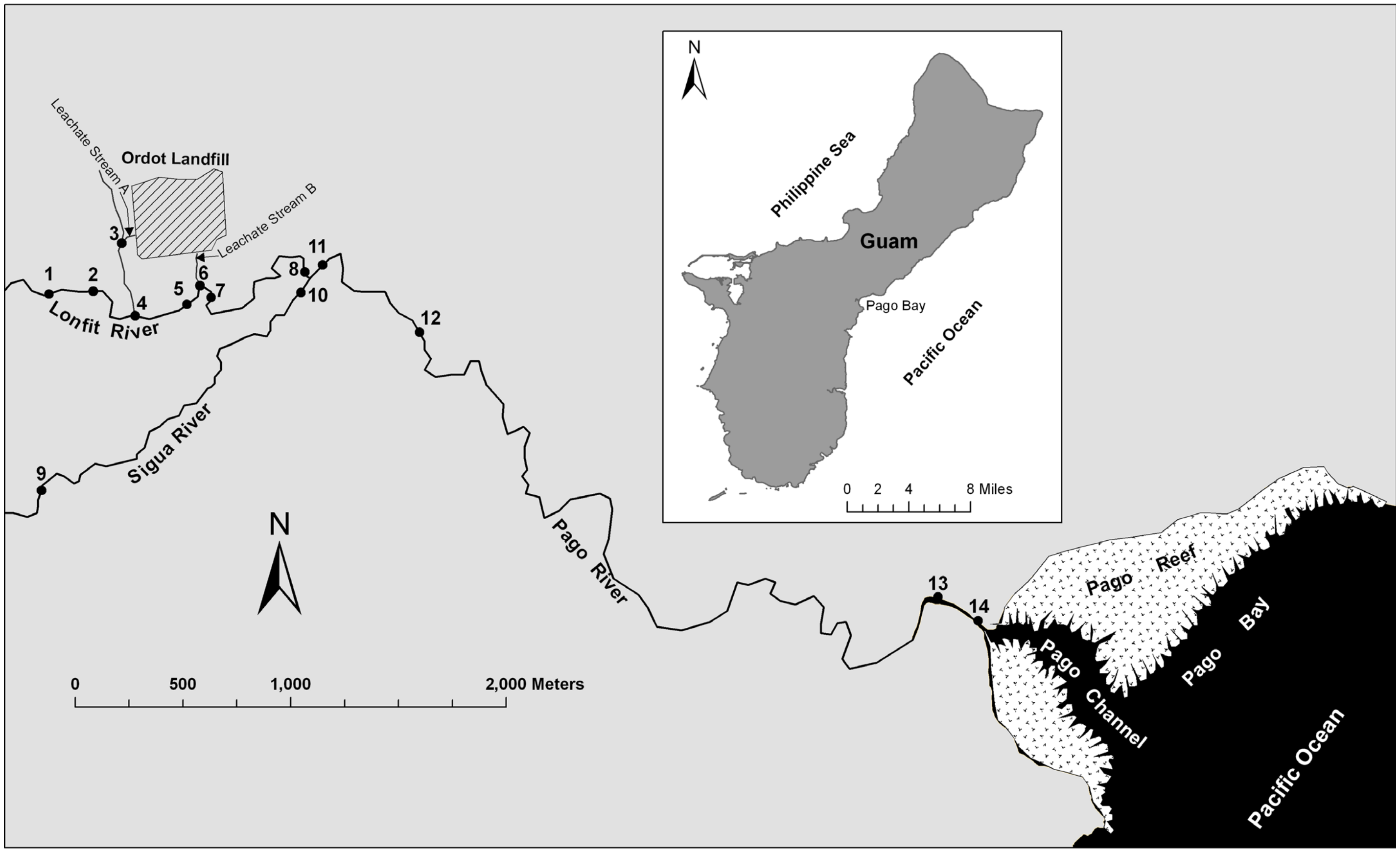

Figure 1: Map of Guam (13°28'N, 144°45'E: inset) and Pago River watershed showing sediment sampling sites. See text for details on sediment sampling sites within Pago Bay. Biota samples were collected on an opportunistic basis throughout the study area

3 Results and Discussion

3.1 Sediments

The heavy metal data for all sediments analyzed during the present study are summarized in Table 1. Sediment geomorphic heterogeneity accounted for some of the elemental variability observed between sites. Stream sediments from within the Pago River watershed, for example, were largely composed of volcanic detrital material and were naturally enriched with iron, manganese, copper, chromium, mercury, nickel and zinc compared with their bioclastic counterparts found in Pago Bay. The latter sediments, derived from foraminifera, coral, shells, *Halimeda* debris and calcareous red algae[6], were particularly abundant at the northern end of the bay. The southern end, by way of contrast, was dominated by volcaniclastic, alluvial deposits discharged from the Pago River during wet weather conditions. A mixture of the two sediment types occurred to varying degrees between these two regions of the bay and is reflected in the data sets shown in Table 1.

Leachate stream sediments taken from close to the landfill were conspicuously contaminated with lead and zinc, and some were notably high in copper when compared with river sediments from control sites. Mild mercury enrichment was also indicated here. Levels of all other elements detected were considered to be within the range of normal variability. River sediments immediately downstream of the landfill showed little evidence of anthropogenic metal enrichment beyond the leachate stream confluence points. The possible exception here was for copper which was marginally elevated in samples from one of two Lonfit River sites adjacent to the landfill.

Mild lead enrichment was apparent at one site in the Pago River estuary, just seaward of the route 4 highway bridge. While the landfill could not be discounted as a potential source of lead to these waters, past contributions from vehicular emissions in the area were considered to provide a more likely explanation. Additionally, the bridge is a popular fishing station which suggests that lead sinkers may also be a contributory source.

Metals in sediments from within Pago Bay were, for the most part, unremarkable with no evidence of impaction from the landfill. As expected, samples from beach sites impacted by groundwater intrusion were marginally enriched with most of the elements examined. One site at the northern end of the bay showed mild lead, mercury and zinc enrichment that was attributed to stormwater runoff from the University of Guam campus and/or septic tank seepage from the institution's shoreline buildings. A small, highly localized area of mild lead enrichment discovered at the southern end of the bay was the site of disused military firing range and was presumably linked to the past activities that took place here.

3.2 Biota

The heavy metal data for biotic components analyzed during the current study are summarized in Tables 2 and 3 for freshwater and marine samples respectively. Comparative data for similar and related species of marine organisms from elsewhere are presented in Table 4. No such data was available for the freshwater species examined. All referenced data are expressed on a dry weight basis unless stated otherwise.

The heavy metal status of many aquatic organisms reflects that of their immediate surroundings, a characteristic that is frequently used by environmental scientists for pollution monitoring and assessment purposes. If used properly, these so called 'bioindicator species' can provide valuable information about an elements distribution and abundance in a particular environment. Aquatic plants and mollusks are particularly good at this because they possess little if any ability to metabolically regulate their metal uptake against changes in the external environment. Crustaceans, on the other hand, demonstrate some metabolic control over essential elements like copper, zinc, iron and manganese, but respond to non-essential metals like lead, mercury and cadmium. Fish are particularly responsive to mercury in the environment but have limited affinities for other non-essential elements and, like crustaceans, are able to regulate essential elements to within well defined limits[7]. Representatives from all these groups were included in the present study.

Heavy metal concentrations in all freshwater species examined (Table 2) were generally indicative of normal background conditions[8]. Copper and zinc levels in the freshwater plant, *Hydrilla verticilata,* were a little higher than expected and could be a result of metal enrichment from the landfill. Levels of both metals in aquatic plants from non-polluted environments are usually less than 10 µg/g for copper and 5-35 µg/g for zinc[8]. The high copper levels found in the two freshwater snails, *Neritina pulligera* and *N. variegata,* while noteworthy, were most likely due to hemocyanin, a copper based respiratory protein found in the blood of these organisms. The fact that the highest levels encountered came from specimens collected upstream of the landfill supports this contention.

Bioindicator species collected from Pago Bay (Table 3) also exhibited heavy metal profiles reflective of a relatively clean environment when compared with levels found in relatives from polluted waters elsewhere (Table 4). The elevated chromium, copper, lead, silver and zinc concentrations found in aquatic plants and bivalve mollusks from Saipan (Commonwealth of the Northern Mariana Islands), to the north of Guam, are particularly noteworthy in this regard. Not unexpectedly, marginally elevated levels of lead were found in the brown algae, *Padina boryana* and *Sargassum cristafolium,* growing near the old rifle range at the southern end of Pago Bay, while minor increases in zinc were evident in algal species from the northern end of the bay.

4. Concluding Remarks

The study described herein shows the Lonfit and-Pago Rivers to be relatively clean from a heavy metal standpoint. This is somewhat surprising in view of the extended time period over which metal enriched leachate has flowed unabated from the Ordot landfill into the Lonfit River and out into Pago Bay. And yet the evidence is clear; sediments show little enrichment apart from in the leachate streams themselves and around their points of confluence with the Lonfit River. Likewise, metal concentrations in aquatic resources within the watershed fall well below existing federal standards and advisories set by the FDA and EPA for the consumption of fish and shellfish[9, 10, 11].

TABLE 1

HEAVY METALS IN AQUATIC SEDIMENTS FROM THE PAGO RIVER WATERSHED AND PAGO BAY, GUAM (data as µg/g dry wt.)

Site Description	Statistic	Ag	As	Cd	Cr	Cu	Fe	Hg[a]	Mn	Ni	Pb	Zn
Sigua River (Control sites 9 & 10)												
(~2 km and 100 m from confluence point	mean[b]	nc		nc	58.6	58.7	50,549	19.8	1,205	66.7	nc	55.6
with Lonfit R.)	range	all <0.02	-	all <0.02	27.0-85.6	42.8-71.3	43,220-57,681	16.5-25.3	697-1,721	45.1-85.6	<0.50-3.80	45.1-65.7
Longfit River (Control sites 1 & 2)												
(~500 m and 300 m upstream of leachate stream A)	mean	nc		nc	68.3	66.6	55,329	24.6	1,297	87.9	nc	55.8
	range	all <0.02	-	all <0.02	49.5-87.5	60.0-89.4	47,232-62,089	21.6-28.3	1,002-1,703	61.9-124	<0.5-4.10	47.9-65.1
Leachate Stream A (Site 3)												
(~100 m downgradient of landfill)	mean	nc		nc	68.1	59.6	75,927	59	1,831	45.3	58.0	217
	range	all <0.02	-	all <0.02	33.1-97.2	44.1-73.4	62,500-86,064	50.2-69.3	1,251-2,339	29.9-63.8	19.5-116	127-310
Leachate Stream A (Site 4)												
(confluence point with Lonfit R.)	mean	nc		nc	71.7	68.1	58,107	59.5	1,695	82.8	1.08	71.1
	range	all <0.02	-	all <0.02	48.4-107	54.4-73.2	45,197-86,858	50.2-69.9	1,111-2,781	69.8-97.4	<0.5-10.2	51.9-89.0
Leachate Stream B (Site 6)												
(confluence point with Lonfit R.)	mean	nc		nc	74.4	68.5	60,995	44.6	1,927	100	3.36	101
	range	all <0.02	-	all <0.02	54.6-129	60.1-82.9	48,730-71,279	37.2-53.4	1,468-2,513	82.2-110	1.17-16.5	68.0-146
Longfit River (Sites 5 & 7)												
(~250 m and 100 m downstream of nearest	mean	nc		nc	62.1	72.2	56,101	27.2	1,215	101	nc	63.6
leachate stream)	range	all <0.02	-	all <0.02	47.0-78.1	59.4-152	43,308-67,966	19.4-36.7	904-1,504	93.0-118	<0.50-2.25	52.7-73.9
Lonfit-Pago River (Sites 8, 11 & 12)												
(~0.9 km, 1 km and 1.7 km downstream of leachate	mean	nc		nc	62.2	71.2	58,098	21.5	1,142	83.5	nc	66.5
stream B)	range	all <0.02	-	all <0.02	47.6-81.2	59.4-82.6	41,249-86,835	17.1-132	991-1,308	62.7-101	<0.50-2.71	52.6-111
Pago River Estuary (Sites 13 & 14)												
(~6.2 km and 6.5 km downstream of leachate	mean	nc		nc	29.6	42.9	35,451	15.6	719	41.3	1.45	42.6
stream B)	range	all <0.02	-	all <0.02	7.10-77.8	15.2-68.2	17,850-55,588	4.23-46.4	484-1,522	20.1-68.3	<0.50-14.5	19.6-88.2
Pago Bay (40 sites)												
(15 sites, predominantly bioclastic sediment)	mean	nc	0.27	nc	3.22	1.01	440	3.25	21.3	1.1	0.52	1.41
	range	all <0.02	0.09-0.56	all <0.02	1.76-9.05	0.56-2.64	148-1,947	0.81-15.7	10.3-49.6	<0.30-2.97	<0.50-5.23	0.60-16.6
(25 sites, predominantly volcaniclastic sediment)	mean	nc	0.69	nc	7.78	5.42	5,365	5.64	188	6.51	0.7	8.77
	range	all <0.02	0.07-2.39	all <0.02	3.27	1.09-20.3	642-53,278	1.63-18.01	55.2-533	1.29-26.0	<0.50-20.5	1.27-89.5

[a]mercury as ng/g dry weight; [b]geometric mean; nc = not calculable; dashes indicate no data

TABLE 2

HEAVY METALS IN AQUATIC ORGANISMS FROM THE PAGO RIVER WATERSHED, GUAM (data as µg/g dry wt.)

SPECIES	NEAREST SITE	STATISITC	Ag	Cd	Cr	Cu	Fe	Hg[a]	Mn	Ni	Pb	Zn
AQUATIC PLANTS:												
Hydrilla verticillata	Site 11, Pago River	mean[b]	nc	nc	3.45	18.8	2,093	-	2,880	7.48	nc	79.6
		range	all <0.20	all <0.20	2.34-4.63	15.2-23.3	2,092-4,027	-	1,729-3,911	5.46-15.2	all <0.50	44.5-162
SNAILS (whole flesh)												
Neritina pulligera	Site 2, Lonfit River	mean	nc	nc	nc	1,592	702	-	116	nc	2.14	48.7
		range	all <0.15	all <0.15	all <1.00	1,584-1,600	504-978	-	111-124	<1.00-1.30	<1.00-5.12	47.9-49.5
Neritina pulligera	Site 4, Lonfit River	mean	nc	nc	nc	430	417	-	157	nc	4.14	74.6
		range	all <0.15	all <0.15	all <1.00	354-521	332-522	-	120-205	<1.00-1.24	2.59-6.63	70.5-79.1
Neritina pulligera	Site 6, Lonfit River	mean	nc	nc	nc	236	518	-	155	nc	6.27	92.3
		range	all <0.15	all <0.15	all <1.00	145-384	496-542	-	105-229	all <1.00	5.00-7.87	85.7-99.4
Neritina pulligera	Site 11, Pago River	mean	nc	nc	1.48	604	550	-	133	1.39	2.76	105
		range	all <0.19	all <0.19	<1.00-2.83	182-1,290	256-1,012	-	77.3-242	<1.00-2.24	1.16-4.30	75.5-128
Neritina variegata	Site 2, Lonfit River	mean	nc	nc	1.92	25.9	605	-	101	nc	3.79	54.9
		range	all <0.19	all <0.19	<1.00-5.08	18.7-36.0	498-862	-	74.7-136	<1.00-1.46	3.72-3.86	51.4-58.6
Neritina variegata	Site 11, Pago River	mean	nc	nc	2.24	33.9	1,168	-	241	1.55	1.58	49.5
		range	all <0.19	all <0.19	2.86-3.90	30.8-37.3	1,083-1,260	-	187-312	1.37-1.76	1.10-2.26	40.5-60.5
SHRIMP (tail muscle)												
Microbrachium lar	Site 2, Lonfit River	mean	nc	nc	nc	52.8	27.6	2.29	3.75	nc	nc	82.3
		range	all <0.19	all <0.19	all <0.80	47.9-58.1	26.6-28.6	1.53-5.49	3.51-4.01	all <1.00	all <1.00	79.5-85.4
Microbrachium lar	Site 6, Lonfit River	mean	-	-	-	-	-	5.28	-	-	-	-
		range	-	-	-	-	-	2.36-9.12	-	-	-	-
Microbrachium lar	Site 10, Sigua River	mean	-	-	-	-	-	3.75	-	-	-	-
		range	-	-	-	-	-	2.35-6.15	-	-	-	-
Microbrachium lar	Site 8, Lonfit River	mean	-	-	-	-	-	5.78	-	-	-	-
		range	-	-	-	-	-	4.95-6.75	-	-	-	-
FISH (axial muscle)												
Anguilla marmorata (eel)	Site 11, Pago River	mean	nc	nc	nc	1.11	13.4	71.5	1.53	nc	nc	65.8
		range	all <0.19	all <0.19	all <0.80	<1.00-5.66	8.93-17.2	53.7-91.0	<1.00-4.08	all <1.00	all <1.00	51.3-95.9
Awaous guamensis (gobbie)	Site 6, Lonfit River	mean	nc	nc	0.83	1.14	16.4		1.30	nc	nc	107
		range	all <0.19	all <0.19	0.50-1.14	<1.00-1.31	12.8-20.5	-	<1.00-1.67	all <1.00	all <1.00	97.4-115
Awaous guamensis (gobbie)	Site 11, Pago River	mean	0.19	0.19	2.04	1.01	81.6	-	3.71	1.83	2.01	47.6
		range	-	-	-		-	-	-	-	-	-

[a]Mercury concentrations expressed as ng/g wet weight; [b]mean = geometric mean; nc = not calculable; dashes indicate no data

TABLE 3

HEAVY METALS IN AQUATIC ORGANISMS FROM PAGO BAY, GUAM (data as µg/g dry wt.)

SPECIES	STATISTIC	Ag	As	Cd	Cu	Cr	Fe	Hg[a]	Mn	Ni	Pb	Zn
ALGAE (frond):												
Acanthophora spicifera	Mean[b]	nc	0.56	0.2	2.13	0.56	470	1.7	11.3	3.75	nc	4.39
	Range	all <0.15	0.20-1.72	<0.07-0.47	1.22-3.15	<0.11-1.98	192-877	1.09-2.83	6.38-21.6	3.05-5.20	<0.30-1.36	3.14-8.04
Gracilaria salicornia	Mean	nc	1.55	nc	0.78	0.54	66.9	2.48	11.3	0.3	nc	4.9
	Range	all <0.26	1.43-1.67	all <0.26	0.47-1.17	0.26-1.15	35.2-145	1.74-3.48	7.6-17.5	<0.16-1.07	all <0.58	2.92-8.71
Padina boryana	Mean	nc	3.54	nc	1.58	0.48	672	1.73	45.1	2.29	nc	3.77
	Range	all <0.18	1.96-11.0	<0.14-0.32	0.74-4.65	<0.21-2.14	262-1828	0.59-2.97	19.0-108	1.56-3.36	<0.27-13.8	2.03-8.27
Turbinaria ornata	Mean	nc	20.4	nc	0.7	nc	238	3.25	6.4	1.15	nc	2.21
	Range	all <0.26	8.58-36.9	<0.14-0.30	0.30-1.95	<0.16-1.83	48.7-1207	1.75-5.20	2.88-18.2	0.49-3.22	<0.30-1.62	1.51-4.37
Sargassum cristafolium	Mean	nc	85.4	nc	0.88	nc	96.4	2.21	8.45	2.82	nc	2.19
	Range	all <0.19	70.9-97.3	<0.14-0.31	0.46-1.63	<0.14-1.20	17.3-653	1.12-3.40	2.61-40.7	0.68-8.00	<0.18-5.22	0.76-4.83
Sargassum polycystum	Mean	nc	15.8	nc	1.82	1.39	911	2.29	61	3.15	nc	3.69
	Range	all <0.26	9.61-22.4	<0.14-0.29	0.92-2.79	0.60-2.66	236-1820	1.72-3.61	29.4-101	1.48-5.01	<0.3-1.51	2.56-7.01
SEAGRASS (blade):												
Enhalus acoroides	Mean	nc	0.28	nc	1.95	nc	107	1.73	11.2	2.2	nc	8.95
	Range	all <0.19	0.10-1.2	all <0.19	0.74-5.7	<0.15-0.60	59.1-273	1.13-3.6	4.61-36.4	1.26-4.30	<0.29-1.10	4.96-18.4
SEACUCUMBERS:												
Holothuria atra (BWM)	Mean	nc	3.36	nc	1.21	0.19	23.5	2.02	0.51	0.17	nc	14.7
	Range	all <0.14	1.77-5.83	all <0.14	0.89-1.62	<0.09-0.32	17.5-39.5	1.13-4.48	0.28-0.82	<0.09-0.37	all <0.28	12.8-17.8
Holothuria atra (HS)	Mean	nc	4.93	nc	5.11	2.85	92.2	16.2	2.06	0.6	0.91	104
	Range	all <0.8	1.29-11.2	all <0.8	3.75-6.37	0.67-13.6	54.4-292	1.75-52.3	1.00-3.92	0.34-1.16	0.38-<1.10	56.9-301
BIVALVES (whole flesh):												
Asaphia violascens	Mean	0.11	-	0.11	0.16	7.61	971	-	15.2	5.87	0.81	72.9
	Range	-	-	-	-	-	-	-	-	-	-	-
Gafrarium pectinatum	Mean	0.14	-	1.14	0.21	17.0	386	-	22.9	16.4	0.27	59.6
	Range	-	-	-	-	-	-	-	-	-	-	-
Quidnipagus palatum	Mean	nc	16.8	nc	17.5	nc	846	36.9	6.81	nc	0.43	222
	Range	all <0.13	9.71-27.2	all <0.13	4.26-68.5	<0.12-0.46	601-1292	21.9-62.4	2.92-23.1	<0.12-0.46	<0.20-0.89	93.6-341
Scutarcopajia scobinata	Mean	0.34	-	0.34	1.01	6.07	2178	-	6.07	9.09	0.64	50.6
	Range	-	-	-	-	-	-	-	-	-	-	-

[a]Mercury concentrations expressed as ng/g wet weight; [b]mean = geometric mean; nc = not calculable; dashes indicate no data; BWM = body wall muscle; HS = hemal system

TABLE 4

HEAVY METALS IN SIMILAR AND RELATED SPECIES OF MARINE ORGANISMS FROM CLEAN AND POLLUTED ENVIRONMENTS ELSEWHERE (data as µg/g dry wt.)

SPECIES	LOCATION	STATUS	Ag	As	Cd	Cr	Cu	Fe	Hg[a]	Mn	Ni	Pb	Zn	REFERENCE
ALGAE (frond):														
Acanthophora spicifera	Pago Bay, Guam	Clean	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	Clean to Polluted	<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	12
Padina australis	Gt. Barrier Reef, Australia	Clean	-	-	0.4-0.6	-	2.0-3.0	-	1-4	-	1.0-1.4	<0.9-5.0	3.8-9.5	13
Padina boyana	Pago Bay, Guam	Clean	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 tetrostromatica	Townsville Harbor	Polluted	<0.1	-	<0.4	31.5	58.9	6429	-	818	13.1	108	440	14
Padina sp.	Apra Harbor, Guam	Clean to Polluted	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	15
Padina sp.	Tanapag Lagoon, Saipan	Clean to Polluted	<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	12
Sargassum cristafolium	Pago Bay, Guam	Clean	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 pallidum	Pacific coastal waters	Clean to Polluted	-	-	1.3-5.1	-	1.6-4.3	-	-	-	-	5.5-25.2	2.7-95.9	16
Sargassum polycystum	Pago Bay, Guam	Clean	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	Clean	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	12
Sargassum sp.	Townsville, Australia	Clean	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	14
SEAGRASS (blade):														
Enhalus acoroides	Pago Bay, Guam	Clean to Polluted	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	Clean to Polluted	all <0.20	0.03-0.19	0.15-0.60	<0.30-0.40	2.15-48.0	-	0.60-2.34	-	0.60-2.34	<0.22-2.05	20.0-33.0	12
SEACUCUMBERS:														
Holothuria atra (BWM)	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 (HS)	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 (BWM)	Apra Harbor, Guam	Clean to Polluted	all <0.12	13.6-23.2	<0.1-0.1	<0.1-0.3	0.7-1.2	-	7-8	-	<0.2	all <0.3	15.5-17.9	15
Holothuria atra (HS)	Apra Harbor, Guam	Clean to Polluted	<0.35-4.90	7.24-28.3	0.25-0.26	2.21-8.58	4.70-5.19	-	49-88	-	all <0.50	all <0.92	120-180	15
Holothuria atra (BWM)	Tanapag Lagoon, Saipan	Clean to Polluted	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	12
Holothuria atra (HS)	Tanapag Lagoon, Saipan	Clean to Polluted	<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	12
BIVALVES (whole flesh):														
Asaphia violascens	Pago Bay, Guam	Clean	0.11	-	0.11	0.16	7.61	971	-	15.2	5.87	0.81	72.9	This study
Asaphia violascens	Tanapag Lagoon, Saipan	Polluted	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	12
Gafrarium pectinatum	Pago Bay, Guam	Clean	0.14	-	1.14	0.21	17	386	-	22.9	16.4	0.27	59.6	This study
Gafrarium pectinatum	Tanapag Lagoon, Saipan	Clean to Polluted	<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	12
Gafrarium tumidum	Townsville, Australia	Clean to Polluted	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	-	14
Quidnipagus palatum	Pago Bay, Guam	Clean	<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	Clean to Polluted	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	12

[a]mercury concentrations as ng/g wet weight; dashes indicate no data; BWM = body wall muscle; HS = hemal system

Since Guam has a tropical wet-dry climate, metal inputs from the landfill into the Lonfit River are seasonally dependant. During dry weather, low stream flow conditions prevail and metals entering the river from the landfill tend to accumulate in bottom sediments close to zones of leachate impaction. During the wet season the picture is very different. The Lonfit River, like most narrow, steep-banked streams that drain the volcanic uplands of Guam, is periodically subjected to flash flooding. Under such conditions, stream flow is of sufficient to scour debris from the river bed, erode embankments and dislodge trees and other vegetation found growing there. On such occasions, pockets of contaminated sediment that accumulate in the leachate streams, and at their points of confluence with the Lonfit River, are swept downstream into the Pago River estuary and out into the bay. This process naturally cleanses the Lonfit-Pago river system of potentially persistent contaminants that might otherwise accumulate in bottom deposits and impact aquatic food chains in these waters.

At greater risk of metal contamination, therefore, are the Pago River estuary and Pago Bay itself. Sediment deposition in these areas is much more pronounced, particularly in and around the river mouth. However, the absence of any significant heavy metal build-up in this region suggests the same natural cleansing principles operate, although the process may be restricted to major storms (typhoons) that approach from the eastern (windward) side of the island. We speculate that such storms are instrumental in purging the area of old alluvial deposits and any contaminants that have accumulated therein during the intervening period. Certainly, stream flow into the bay under such conditions is of sufficient volume and velocity to create an extensive sediment plume that is funneled into deeper waters beyond the reef margin via the reef channel (see Fig. 1). Hence, bottom deposits in this region may well be the ultimate sink for metal contaminants mobilized downstream from the landfill. If such is the case, then benthic species, particularly sessile forms and those with restricted home ranges, could be the most vulnerable biotic components in the area in terms of metal exposure. The analysis of sediments and biota from this region would therefore be of interest and is seen as a logical extension of the current work.

Acknowledgements

We are indebted to Wendy Mendiola, Jackie Holbrook and Walter Kelley III for field and laboratory assistance, and to Rick Wood for overseeing the chemical analysis. This work was jointly funded by the Department of Interior via the Water Resources Research Institute Program of the U.S. Geological Survey (Award No. 01HQPA0010), administered through the Water and Environmental Research Institute of the Western Pacific (WERI) at the University of Guam; the National Oceanographic and Atmospheric Administration (NOAA) through the Guam Coastal Management Program, Guam Bureau of Statistics and Plans (Award Nos. NA17OZ232) and the Guam Coral Reef Initiative, Guam Department of Agriculture (Award Nos. NAO4NOS4260299).

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