COASTAL POLLUTION AND POTENTIAL BIOMONITORS OF METALS IN MAURITIUS

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Abstract. Contaminant metals are potentially toxic, accumulate in the sediment, are bioconcentrated by organisms and may cause health problems to humans via the food chain. Discharge of industrial wastewaters and untreated sewage pose a particularly serious threat to the coastal environment of Mauritius, but very little information exists on contaminant metals. This study aimed principally to assess such contamination by (i) reviewing available data, (ii) examining the results of metal (Cd, Cu, Cr, Pb and Zn) analysis in (a) seawater, sediment and biota from an island-wide survey of 20 sites in 1999–2000, (b) seawater from a water quality survey (high tide and low tide) in 2003 of a 10 km stretch of sewage-impacted coast.

UNEP reference methods were used for sample collection and processing, and metal analysis was perfomed by flame atomic absorption spectrophotometry (AAS). Results were compared with established guidelines and data reported from elsewhere, and examined for suitable plant and animal species as biomonitors.

The pioneering study by SOGETI (1995) provided indications of high marine sediment contamination in Mauritius compared to data reported from elsewhere. The 1999–2000 islandwide survey indicated even higher sediment contamination, namely at hotspots, requiring the use of sediment quality guidelines (SQG) for monitoring and assessment. Maximum metal concentrations from these two studies were as follows: 736 μgg^{-1} Zn, 329 μgg^{-1} Mn, 98.1 μgg^{-1} Pb, 93.38 μgg^{-1} Cu, 91.39 μgg^{-1} Cr, 65.53 μgg^{-1} Sn and 55.01 μgg^{-1} Cd. Seawater contamination corresponded closely to the pattern of sediment contamination, both showing a downstream and away-from-the-outfall gradient. Applicable guidelines for seawater were exceeded at more than 50% of the sites around Mauritius with maximum concentrations of Cr, Cu, Zn, Pb and Cd as follows: 0.41, 0.352, 0.312, 0.247 and 0.232 mgl^{-1}, respectively. Maximum concentrations of Cu, Cd, Zn, Pb and Cr along the sewage-impacted shoreline occurred during low tide as follows: 0.454, 0.329, 0.259, 0.138 and 0.123 mgl^{-1}, respectively. The recommended limits for Cu, Cd and Zn were exceeded in all the samples. High tissue accumulation by marine biota corresponded to high levels of seawater and sediment contamination at hotspots. Species showing the highest potential as biomonitors (namely *Ulva lactuca, Enteromorpha ramulosa,Crassostrea cuculatta, Isognomon isognomon and Echinometra mathaei*) were identified based on their common occurrence, high bioconcentration potential and successful utilization in studies elsewhere.

Enhanced levels of contaminant metals were recorded and suitable biomonitors were identified. It is advocated that a rigorous use of the suite of biomonitors proposed in this study and others later will allow identification of the different metal sources as well as provide an improved assessment of the magnitude of metal contamination in the coastal marine environment of Mauritius.

Keywords: biomonitoring, contaminant metals, coastal hotspots, Mauritius

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1. Introduction

The nearshore marine ecosystem is a dynamic environment impacted by many activities, especially the coastal waters and sediments adjacent to major metropolitan areas. Although heavy metals are natural constituents of the marine environment, inputs are considered to be conservative pollutants as they are not subject to bacterial attack or other breakdown (Clark, 1989). A variety of trace metals are essential for biological processes in all organisms (e.g. Hunter *et al*., 1997), but excessive levels can be detrimental by acting as enzyme inhibitors (Rainbow, 1985; Bryan and Langston, 1992). Of particular concern to water systems are the non-essential elements such as Cd, Pb, As, Se, Hg, Cr, Sn (Hopkin, 1989) because they are potentially toxic to aquatic organisms above a threshold availability (Nemerrow, 1985; Kennish, 1994). Currently, anthropogenic inputs of metals to the sea exceed natural inputs (e.g. Connell *et al.*, 1984) and a large part of it ultimately accumulates in the sediment (Yeats and Bewers, 1983). The sediment is quantitatively as important as the water column and biota as major reservoirs of heavy metals. Measurement in all three media (water, sediment and biota) is considered essential for monitoring and assessment purposes (Everaarts *et al*., 1994; Saiz-Salinas *et al*., 1996; Goh and Chou, 1997).

Uptake and accumulation of metals from the surrounding water by absorption and diffusion across the body surfaces and ingestion of food and particulates pose a major problem with respect to their effects on biota and humans as they are bioconcentrated up the food chain (Mance, 1987). The ability of some marine organisms to accumulate heavy metals to very high tissue and body concentrations (e.g. by factors of 10 to 10) renders them very useful as bioindicators. Interest in such organisms for assessment and monitoring of marine pollution is growing worldwide, and cosmopolitan biomonitors frequently include benthic invertebrates and seaweeds (e.g. Phillips, 1976; Orren *et al*., 1980; Martincic *et al*., 1986; Rainbow and Phillips, 1993; Rainbow, 1995; Shuklin and Kavun, 1995). Uptake of predominantly soluble forms of metals (e.g. Cu, Zn, Cd) by organisms occurs mainly from the water phase and is proportional to the metal ion activity in the water (Engel *et al*., 1981; Sanders *et al*., 1983). Some of the disadvantages associated with measurement of dissolved concentrations (e.g. variation over time, tidal cycle, dilution due to run-off, cost, bioavailbility) are overcome by the analysis of sediments. Heavy metals accumulate in sediments and measurement is much easier and less susceptible to accidental contamination (Rainbow, 1995). However, metal uptake from sediment fractions does not occur and there is restricted availability of sediment-bound metals to benthic biota (Samant and Vaidya, 1990). Thus, a consistent correlation does not always exist between the body burdens of heavy metals in organisms and concentrations in the sediment. Although uptake of a specific metal species does not depend directly on metal levels in the surface sediment (Everaarts *et al*., 1994) or prey tissue (Nott and Nicolaidou, 1994), studies of metal bioaccumulation from sediments have proved to be useful tools for assessing ecological risks from metal-contaminated sediment and for investigating influences on bioavailability and mobility of metals in sediments (Woodward *et al*., 1994; Ingersoll *et al*., 1994).

This paper aims principally to provide an assessment of contaminant metals and identify potential biomonitors in the coastal marine environment of Mauritius based on (a) a review of published data on the subject and comparison with results reported from elsewhere in the literature, (b) an examination of metal analysis data on seawater, sediment and biota from 20 sites around the island during 1990–2000, (c) an examination of data on seawater analysis from a 10 km stretch of sewage-impacted coast in 2003, and (d) comparing with applicable guidelines and standards where they exist.

2. The Coastal Marine Environment of Mauritius and Pollution

Mauritius island (20°S, 57°E; 1860 km^2 area), formed by volcanic activity in the southern part of the Mascarene Plateau (Western Indian Ocean) about 800 km east of Madagascar (Figure 1), has a 300 km long coastline which is surrounded by 243 km^2 of lagoons bounded, for the most part, by fringing coral reefs. The climate is tropical and the dominant winds blow mostly from south east. The lagoons are shallow (generally 1–2 m average depth) and discontinuous, and range in size from 0 to 8 km between beach and reef. Lagoon morphology varies from single lagoons consisting of a sandy beach and a reef zone, to complex systems comprising a variety of habitats: beaches, mangroves, sand or mud swamps, lagoon channels, seagrass beds, coral colonies, sand beds and a reef zone (Fagoonee, 1990). Sediments in the lagoons are derived from terrigenous inputs at river mouths as well as carbonate inputs from the reef complex. Productive seagrasses often grow close to beaches where they help to stabilise sediments and provide nursery grounds for reef species (Daby, 2003a). Sandy beaches and dunes occupy about 1.7% of the total surface area of the island (i.e. 31 km^2 or 3100 ha) and nearly all beaches consist of white biogenic carbonate sand. Dense fields of mixed coral colonies form patch reefs in the lagoons, often developed directly from the reef flat and covering extensive lagoon areas. Coral colony height varies from 0.2 to 1 m and the coverage for a single patch may extend up to 1 km^{-2}. The colonies are exposed only during the lowest spring tides. Distribution of the coral patches is limited by the influx of terrigenous sediment, river freshwater and/or underground freshwater seepage into the lagoon. The patches are often surrounded by wide areas of sand. Area cover estimates of some benthic habitats within the coastal zone of Mauritius indicate that sand covers 70 km^2; mixed sand and algae 15 km^2; seagrasses 30 km^2; lagoonal corals 45 km^2 and dead coral 7.52 km^2 (Turner *et al*., 2000).

With agriculture, industry, and tourism (mainly marine-based) as its principal economic bases, Mauritius (1.2 million inhabitants) has enjoyed two decades of rapid development, but now the natural resource base of the coastal zone is increasingly being degraded by terrestrial inputs from intensified urbanization

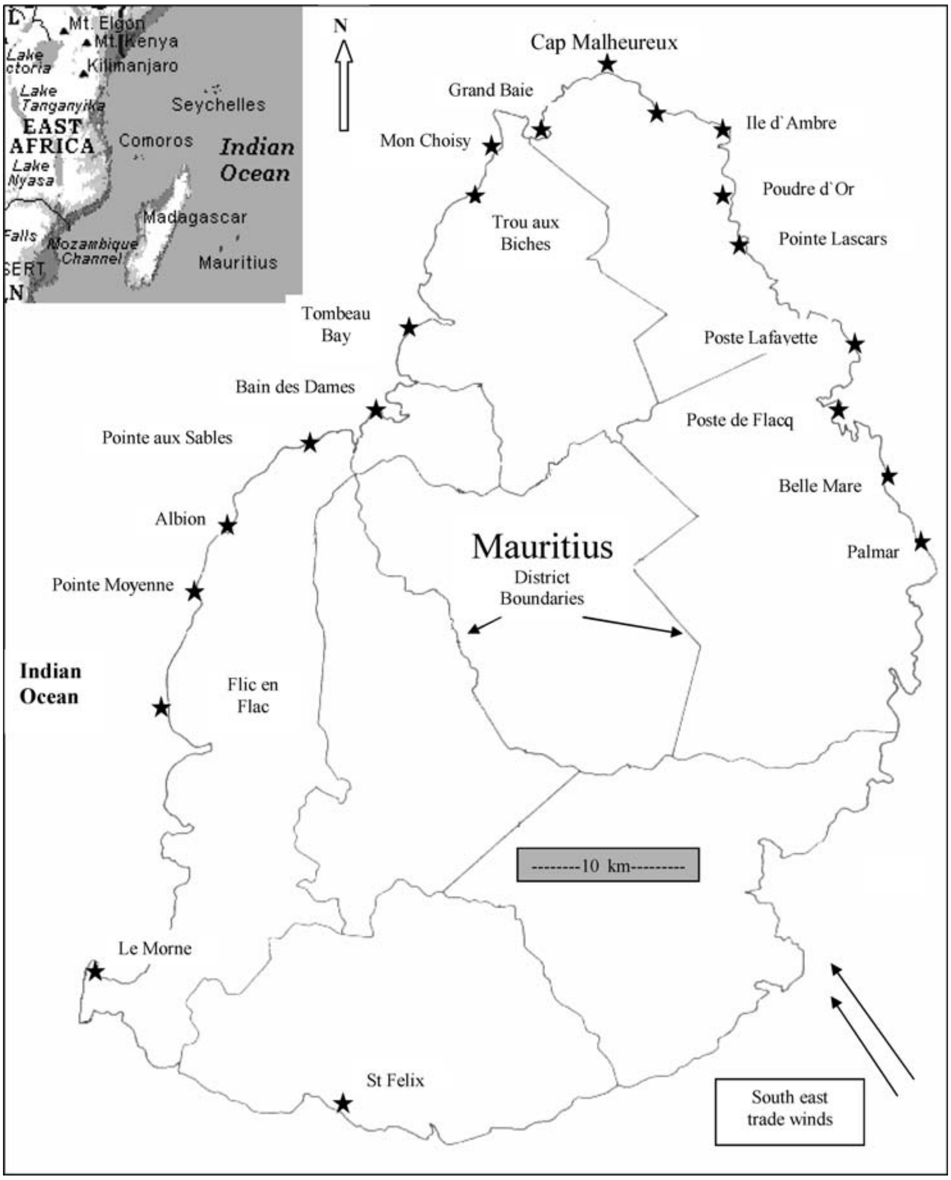

Figure 1. Sites for seawater, sediment and biota sample collection around Mauritius, 1999–2000.

(Daby *et al*., 2002; Daby, 2003b). Manufacturing industries discharge substantial amounts of dyestuff, heavy metals and complex chemical compounds into the wastewater systems, streams and rivers, and the majority of these pollutants accumulate in estuarine and lagoon sediments (Daby, 2001). Concluding on coastal and surface water quality in Mauritius, Severn Trent International (STI), UK (1993) reported that industrial waste waters (namely textile effluents) pose a particularly serious threat to the coastal environment and to public health. Untreated sewage from 60% of the population is deposited via outfall only 500 m offshore at various sites along the western coast, namely in the vicinity of Port Louis harbour e.g. at Pointe aux Sables, Pointe Moyenne, Roche Bois (Hartnoll, 1994). A shift has been detected in soft-bottom macroinfauna to dominance of nematodes and polychaete worms in Pointe aux Sables lagoon (Thomassin *et al.*, 1998), indicating the prevalence of acute pollution in the ecosystem. Pollution problems are exacerbated by natural seepage and percolation of underground freshwater often contaminated with untreated domestic sewage and effluents through the coastal substrate into the lagoons (Muller, 1991; Daby *et al.*, 2002). The Mauritian Government has not yet adopted effluent water quality standards for disposal, so more often than not industrial effluents would carry pollutant loads far in excess of acceptable limits (Water Management Consultants – WMC, 2000). Receiving water quality standards were adopted in Mauritius in April 1999 for coastal conservation, recreation, fisheries and for coastal areas which act as receiving body for industrial and agricultural discharges. Systematic studies on pollution sources, the pollutants involved and their environmental impact has however not been undertaken, and data on coastal contaminant metals in particular are indeed very rare. Although metal contamination of surface waters and surficial sediments in Mauritius is only recent (Ramessur *et al.*, 1998, 2001), higher levels of Pb, Cr and Zn (although below the reference standards adopted) were reported by Ramessur and Ramjeawon (2002) near point sources from industries as well as in the estuary than upstream in the nearby St. Louis River, which discharges in the bay north of Pointe aux Sables lagoon. Mungur and Choong Kwet Yive (1998) suggested vehicular emission on the main M1 motorway as a major source of Pb contamination in the Grand River North West (G.R.N.W, Figures 2 and 4) catchment area.

3. Materials and Methods

3.1. Assessment of sediment contamination from a review of reported data

SOGETI (1995) pioneered to measure the content of Cu, Zn, Ni, Pb, Cr and Mn using flame AAS in samples of marine sediment collected from Pointe aux Sables lagoon (Transect TR2 to TR5: Figure 2) and Pointe aux Caves on the west coast of the island. Discharge of untreated sewage just outside the coral reef via an old outfall located south of Transect TR5 and inputs from the G.R.N.W. were considered to constitute the principal sources of contamination, which is generally carried southward by the main oceanic current flow (WMC, 2002). The results of the study summarised in Table I were examined, and since guidelines have not been developed in Mauritius for assessment of sediment quality, a direct comparison was

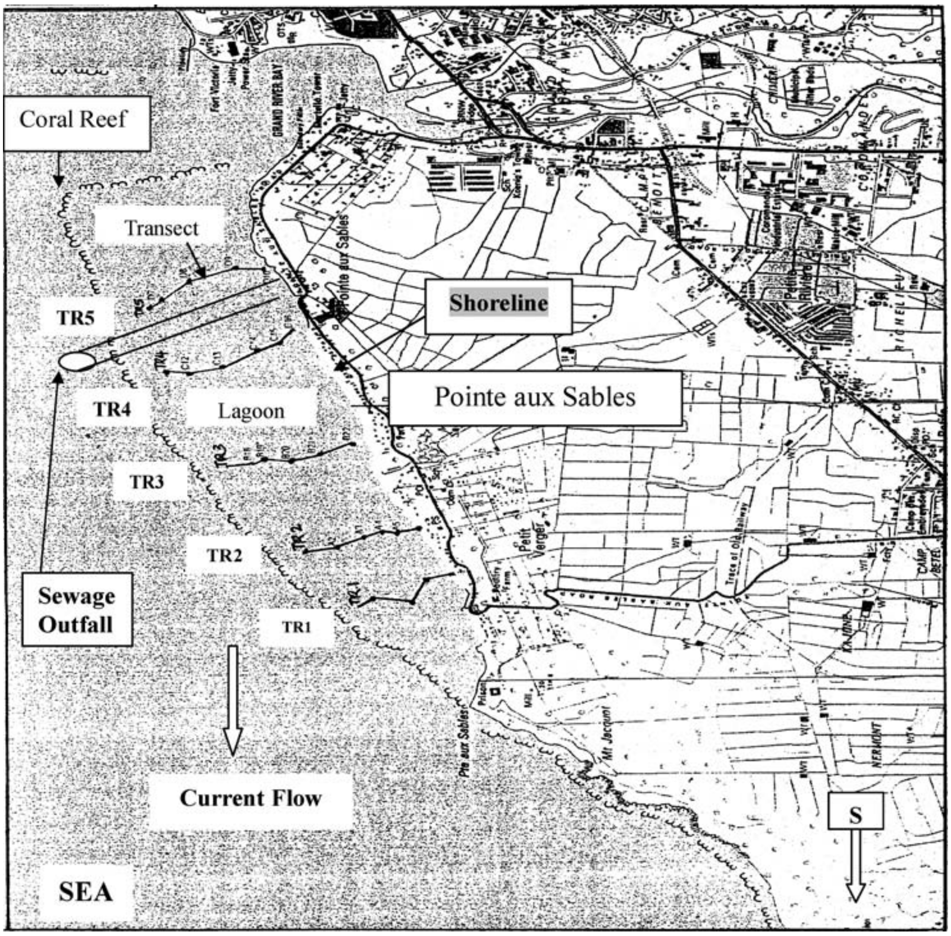

Figure 2. Sampling transects used by SOGETI (1995) in Pointe aux Sables lagoon for sediment collection.

made with literature data (namely for Cu, Cr, Pb and Zn) reported from sites in Europe, Asia, Africa and the Middle East (see Table II).

3.2. Assessment of metal content in sediment, seawater and marine organisms: 1999–2000

A rigorous study of 20 coastal sites (Figure 1) around Mauritius was undertaken, with 4 re-visits of each site during the period June 1999 to May 2000. The objectives were to (i) establish the range of metal (Cd, Cu, Cr, Pb and Zn) concentrations in samples of nearshore seawater, sediment and tissues of common inshore organisms, (ii) compare concentrations in seawater with the applicable 'Guidelines for coastal

TABLE I

Metal concentrations in samples of marine sediment (μgg^{-1} dry weight) reported by SOGETI (1995) from Pointe aux Sables and Pointe aux Caves (west coast)

Transects (TR2–TR5)	Outfall Distance (m)	Shore Distance (m)	Copper (μgg^{-1})	Zinc (μgg^{-1})	Nickel (μgg^{-1})	Lead (μgg^{-1})	Chromium (μgg^{-1})	Manganese (μgg^{-1})
TR2	1440	409	23	699	10.7	47.8	26.7	87 [2pt]
	1476	274	22.3	369	7.4	26.7		73
	1515	178	23.3	325	6.7	25.8		77
	1558	142	19.8	272	4.3	22.4		71
TR3	818	544	24.8	736	18	34	28.2	89
	829	498	24.5	540	10.5	30.7		83
	925	398	22.8	350				
	999	281	23.5	272	7.2	26.5		79
	1109	117	22.5	266	2	25.8		75
	1109	117	22.9	230	3.2	23.4		73
TR4	284	601	34.7	606	23.5	34.9	34.7	114
	427	459	32.8	406	11.9	25.3		101
	605	274	26.5	253	8.7	18.4		96
	693	171	23.5	275	7.3	22.1		100
	782	89	22.1	225	4.2	16.9		95
TR5	398	629	23.5	125	9.4	29.1	30.4	116
	619	409	27.7	127	8.7	29.4		112
	619	409	29.4	289	8.2	29.4		120
	789	196	31.2	404	12.9	30.3		117
	843	114	34.8	438	14.3	36.6		136
Metal concentration range in Pointe aux Sables lagoon			19.8–34.8	125–736	2–23.5	16.9–47.8	26.7–34.7	73–136
Pointe aux Caves	30 m depth		47.7	134	52	38.2	84	329
	15 m depth		23.7	118	14.3	22.2	45.4	158

water quality for Mauritius' published by the Ministry of the Environment (1999), (iii) compare concentrations in the sediment with the results reported in Tables I and II, and (iv) propose appropriate/suitable bio-indicators of these toxic metals for use in monitoring studies. Table III lists the species of marine plants and animals which were sampled for analysis and their sites of collection. These included species of green, brown and red algae, seagrasses, sponges, snails, bivalves, and a sea urchin. Water samples were collected from 30 cm below the surface at the same spots where the surficial (0–3 cm) sediment was also removed at a water depth of about 1 m. Sampling and procedures for chemical analysis of metals in water, sediment and organisms were performed following the methods for trace metals described in UNEP (1982) and UNEP/IOC/IAEA (1984, 1985a,b) reports. Quality assurance

TABLE II

Metal concentrations in coastal sediments (μgg^{-1} dry weight) of Mauritius and from various reported sources

		Metal content (μgg^{-1} dry weight) in surface sediment from marine environments					
Country	Reference	Cadmium	Copper	Chromium	Lead	Tin	Zinc
Hong Kong: Tolo Harbour	Chu *et al.*(1990)	2–7	2–7				10–180
Hong Kong: Sai keng	Tam and Wong (1995)		42		650		150
Hong Kong: Hebe Haven	Lo and Fung (1992)	0.02–3.6	5–42		12–51		20–132
Malaysian Coast: Mersing	Ismail *et al*. (1995)	0.38	7.61		27.52		38.97
Kuala Terengganu		0.28	1.79		6.16		13.86
Melaka		0.54	8.17		18.46		42.43
Tanjung keling		0.27	3.81		15.38		17.05
Kuala Sepetang		0.35	4.91		26.14		33.91
Greece: East coast	Nicolaidou and Nott (1998)	0.1	13.2	677.6			152.5
Greece: Thermaikos Gulf	Voutsinou-taliadouri and Satsmadjis (1983)	0.22–5.1	8–60	18–250			40–345

(*Continued on next page*)

TABLE II
(*Continued*)

Country	Reference	Metal content (μgg^{-1} dry weight) in surface sediment from marine environments					
		Cadmium	Copper	Chromium	Lead	Tin	Zinc
Kenya coast	Everaarts and Nieuwenhuize (1995)	0.01–0.34	3–42		0.5–15.8		2–17
Java, Indonesia: East coast	Everaarts (1989)	0.03–0.45	6–54		5–46		30–125
Thailand: Pattani Bay	Everaarts *et al.* (1994)	0.01–0.04	22–27		79–97		55–62
Spain: Portman Bay	Auernheimer and Chinchon (1992)				15–1802		12.5–5950
Spain: Bidasoa Estuary	Saiz-Salinas *et al.* (1996)	0.4–1.5	36–221	32–79	70–298		219–736
Kuwait coast	Bu-Olayan and Subrahmanyam (1998)		12.5–149.3		10.6–35.6		90.7–280
Singapore	Goh and Chou (1997)		1.4–1781		1.4–82.2		94.9–281.3
Ireland: Donegal Bay	Minchin *et al.* (1997)					0.7–0.8	
Mauritius: Pointe aux Sables and Pointe aux Caves	(SOGETI, 1995)		19.8–47.7	26.7–84	16.9–47.8		118–736
Islandwide	(this report)	0.03–55.01	0.66–93.38	3.28-91.39	2.71–98.1	2.28–65.53	9.85–661

TABLE III

Species of marine biota sampled for metal analysis and their sites of collection, 1999-2000.

	Marine plants																Sponges			Marine animals																
Survey sites (see Figure 2)	*Ulva lactuca*	*Ulva fasciata*	*Ulva reticulata*	*Enteromorpha ramulosa*	*Sargassum binderi*	*Padina boryana*	*Turbinaria ornata*	*Thalassodendron ciliatum*	*Halodule uninervis*	*Syringodium isoetifolium*	*Caulerpa sertularoides*	*Caulerpa serrulata*	*Sarconema filiforme*	*Galaxaura oblongata*	*Galaxaura marginata*	*Galaxaura canaliculata*	*Biemia fortis*	*Perle bleu*	*Brown tree*	*Morula granulata*	*Nerita undata*	*Cypraea tigris*	*Cypraea caputserpentis*	*L. littorea(0.5-1 cm)*	*L. littorea (1.1-1.5 cm)*	*L. littorea (1.5-2 cm)*	*L. mauritiana (0.6-1 cm)*	*L. mauritiana (1..1-1.5 cm)*	*L. mauritiana (1.6-2 cm)*	*I. isognomon (0-2.5 cm)*	*I. isognomon (2.6-5 cm)*	*Pinna muricata*	*Crassostrea cucullata*	*E. mathaei skeleton (0-2.5 cm)*	*E. mathaei skeleton (2.6-5 cm)*	*E. mathaei skeletn (5.1-7.5 cm)*
Cap Malheureux																x								x	x	x										
Mon Choisy	x								x	x										x	x		x	x	x	x				x	x					
Trou aux Biches	x			x		x	x																											x	x	x
Baie du Tombeau		x																																		
Bain des dames	x			x																																
Pointe aux Sables	x			x									x							x																
Albion									x																											
Pointe Moyenne	x			x																																
Flic en Flacq					x	x								x																					x	
Le Morne					x		x																											x	x	x
Poste de Flacq		x								x					x																		x			
Belle Mare							x												x			x								x	x		x			
Poste la Fayette					x	x		x		x																										
Pointe des Lascars				x													x																			
Poudre d'Or			x		x					x							x	x									x	x	x	x	x		x			
Ile d'Ambre					x	x					x																					x	x			
Grand Gaube											x	x															x	x	x				x			
Palmar	x																										x	x	x							
~~St Felix~~	x																										x	x	x					x	x	x

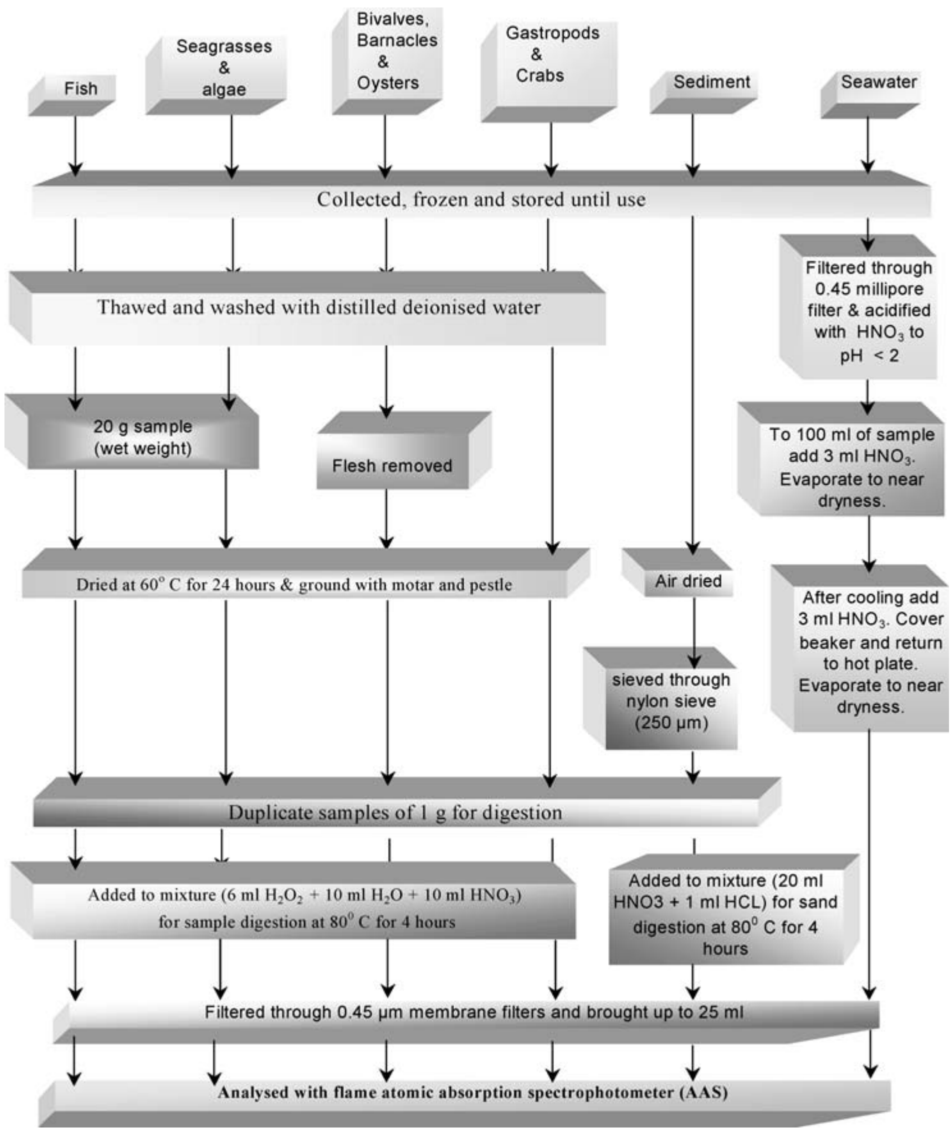

Figure 3. Sample processing procedures for metal analysis by flame atomic absorption spectrophotometry.

and good laboratory practice were ensured by adopting the reference methods of UNEP (1990). Flame AAS (Unicam) was used for measurement of Cu, Cd, Cr, Pb, Zn and Sn. The procedures followed for the different types of samples are illustrated in Figure 3. The precision of the method was determined by analysis of triplicates and is expressed as the coefficient of variation for each element: Cu 4%, Cd 6%, Cr 4%, Pb 6%, Zn 3% and Sn 5%. Accuracy was evaluated by spiking 3 litres of

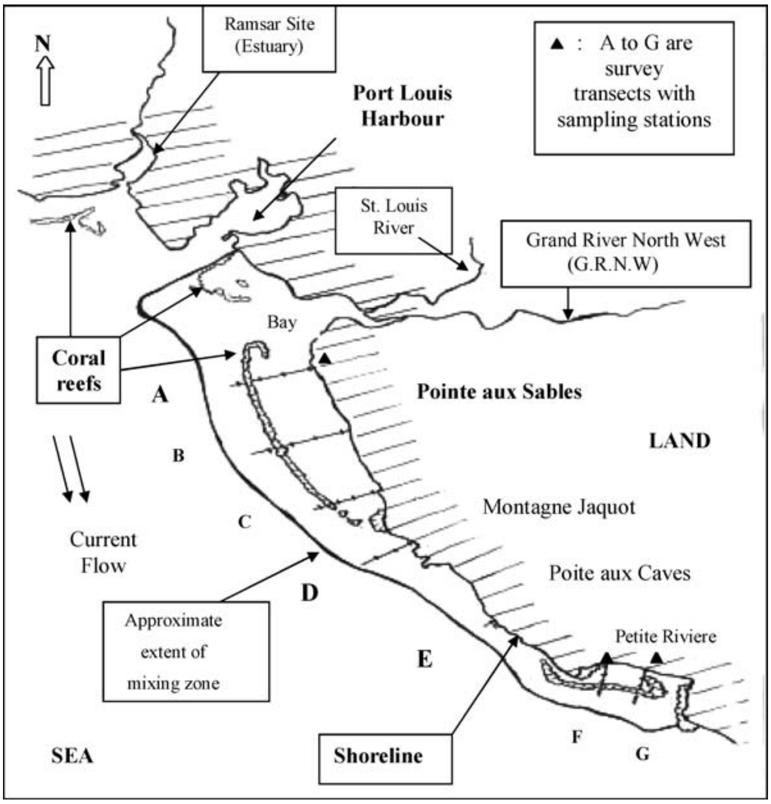

Figure 4. Locations of transects (A to G) for water sample collection along sewage-impacted coast, 2003.

clean seawater stripped of trace metals by passing through a chelating (chelex-100 resin) column with known amounts of the metals. The recoveries were 94% Cu, 95% Cd, 93% Cr, 96% Pb, 94% Zn and 93% Sn.

3.3. Assessment of metals in sewage impacted seawater: 2003 study

To address the problem of coastal pollution, the Wastewater Management Authority started implementation of a major environmental sewerage and sanitation project in 2003, which included the construction of a new wastewater treatment plant at Montagne Jaquot on the west coast a few kilometers south-west of Port Louis harbour (Figure 4). The basic design of the scheme was primary treatment of the effluent, plus chlorination, followed by discharge of the effluent into the ocean via a conventional sea outfall. The project is underway to replace the existing old outfall which discharges raw sewage in the reef zone at Pointes aux Sables (Figure 2) only 500 m from the shoreline. For the first time in Mauritius, a baseline study as an integral part of a comprehensive marine Environmental Management Programme related to a coastal project was initiated. Metal (e.g. Cd, Cu, Cr, Pb and Zn) determination in seawater was a major component of a water quality survey prior to building the new treatment plant and ocean outfall.

Survey sites (Figure 4) within the area which could potentially be affected by the operation of the planned outfall at Montagne Jaquot (an area referred to as the 'mixing zone', which was delimited by WMC, UK (2002) using data based on tidal excursion and surface residual flow) were established. This area extended 6.5 km north-east of the projected outfall (i.e. the beach, lagoon and foreshore at Pointe aux Sables which receives raw sewage via the old outfall), 4.5 km south-west (i.e. the beach, lagoon and foreshore at Petite Riviere), and seawards to the 30 m depth contour. Within this defined area duplicate water samples were collected from a total of 24 stations on 7 transects A to G (see Table IV) covering more than 10 km of the shoreline during 4 to 7 December 2003. The survey design included 4 additional stations at the control site H (Ile aux Benitiers, SW) well away from the above defined area and free from the influence of sewage and industrial effluent so that impacts caused by the outfall could be isolated from general impacts being felt by the marine environment on a wider scale due to other causes. Sampling was done during both low and high water conditions to examine for differences in metal content. The metals were analysed by flame AAS as outlined in Figure 3. To gauge the state of the marine water quality the results were compared with (i) the applicable 'Guidelines for coastal water quality for Mauritius' and (ii) the results obtained from the 1999–2000 study conducted at 20 sites around Mauritius.

4. Results

4.1. Contaminant metals in marine sediment

4.1.1. *Results from SOGETI (1995) Study*

The main results of SOGETI (1995) study summarised in Table I indicated a distinct pattern of metal contamination spatially: (a) higher concentrations occurred along Transects TR4 and TR5 adjacent to the outfall, corresponding to a gradient in the spread of the sewage plume emanating from it, (b) whereas metal concentrations increased towards the coral reef along transects south of the outfall (i.e. TR2 to TR4), the reverse was true for Transect TR5, indicating the plume effect to be flowing southward most of the time. The reef zone would be contaminated more than the inshore area generally, but the reversing current direction at high tide (semi-diurnal tides in Mauritius) would spread the contamination northward and inside the lagoon as well, and (c) the more distant and much deeper sediment at Pointe aux Caves (coral reef absent) had higher concentrations of Cu, Ni, Cr and Mn, confirming the general southward transport of the contamination from the outfall and its deposition further away. These would confirm a widespread contami-

TABLE IV

Summary of water quality monitoring sites, sampling stations and times, December 2003.(HW: high water; LW: low water).

Site	Transect	Station	Position description			Sampling date/time & tidal state
			GPS:	20°S	57°E	
North Pointe aux Sables (south of G.R. N.W. mouth)	A	A1	Nearshore	09–969	27–455	
		A2	Mid lagoon	09–865	27–419	05.12.03
		A3	Back reef	09–695	27–352	Time:
		A4	Outside reef	09–482	27–105	11–13 h (HW)
Mid Pointe aux Sables (public beach)	B	B1	Nearshore	10–196	26–840	17–19 h (LW)
		B2	Mid lagoon	10–040	26–775	1st HW: 1110 h
		B3	Back reef	09–932	26–731	
		B4	Outside reef	09–749	26–628	
South Pointe aux Sables	C	C1	Nearshore	10–414	26–278	
		C2	Mid lagoon	10–363	26–247	04.12.03
		C3	Back reef	10–296	26–218	Time:
		C4	Outside reef	10–096	26–069	11–13 h (HW)
Montagne Jaquot (site for new outfall)	D	D1	Nearshore	10–651	25–659	17–19 h (LW)
		D2	Mid pipeline	10–559	25–599	1st HW: 1050 h
		D3	Pipeline End	10–484	25–530	
Pointe aux Caves	E	E1	Nearshore	11–317	24–738	05.12.03
North Petite Riviere (Albion)	F	F1	Nearshore	12–361	24–237	
		F2	Mid lagoon	12–342	24–194	06.12.03
		F3	Back reef	12–317	24–099	Time:
		F4	Outside reef	12–278	23–934	
South Petite Riviere (Albion)	G	G1	Nearshore	12–829	24–120	11–13 h (HW)
		G2	Mid lagoon	12–824	24–088	17–19 h (LW)
		G3	Back reef	12–804	24–040	1st HW: 1130 h
		G4	Outside reef	12–772	23–854	
Ile aux Benitiers	H	H1	Nearshore	24–856	20–320	

(*Continued on next page*)

TABLE IV
(*Continued*)

Site	Transect	Station	Position description GPS:	20° S	57 ° E	Sampling date/time & tidal state
(control site for water quality)						
		H2	Mid lagoon	24–568	19–880	07.12.03
		H3	Back reef	24–448	19–467	Time:
		H4	Outside reef	24–431	19–255	12–14 h (HW)
						18 1930 (LW)
						1st HW: 0030 h

HW: high water; LW: low water.

nation in the defined area of study which was conducted along the sewage-impacted coastline in 2003 (e.g. Figure 4).

Refering to Table II, Cu concentrations were higher in Mauritius than elsewhere, except Spain (Bidasoa Estuary), Greece (Thermaikos Gulf), Java, Kuwait and Singapore. Pb levels in Mauritius were higher than values reported from Malaysia, Kenya, Java and Kuwait, but Zn concentrations in Mauritius were higher than elsewhere, except Spain (Bidasoa Estuary and Portman Bay). Cr levels were comparable to those in Bidasoa Estuary, which would appear to be the most polluted of the sites listed. These would constitute clear signs for establishing that levels of marine sediment contamination by metals were high in Mauritius at Pointe aux Sables.

4.1.2. *Results from Islandwide (1999–2000) study*

Comparison with data from other countries (Table II) indicated Cd contamination was more abundant in Mauritius (e.g. at Pointe Moyenne with a range of 32.34 – 55.01, mean = 42.96 ± 11.4 μgg^{-1}). High concentrations of Cd were also obtained from Pointe aux Sables (33.33 ± 13.01 μgg^{-1}) and Bain des Dames (35.04 ± 7.57 μgg^{-1}). Excluding these 3 sites, Cd variation would be much lower in the range of 0.03 – 2.04 μgg^{-1} (mean= 0.64 ± 0.35 μgg^{-1}) around the coast of Mauritius. Cu concentrations in Mauritius were higher than elsewhere (except Spain, Kuwait and Singapore). Pb concentrations in Mauritius were higher than elsewhere (except Spain and Hong Kong – Sai Keng), and Zn concentrations were higher elsewhere (except Spain). These observations would again reflect the high metal contamination of the marine sediment at certain hotspots around Mauritius.

Cu, Cr, Pb and Zn were the common metals measured in the marine sediment of Pointe aux Sables during both the 1999–2000 and SOGETI (1995) studies. Table V gives a comparison of the 2 sets of results and highlights the following:

(i) Higher concentration means were obtained for all metals in Pointe aux Sables in the 1999–2000 survey than values reported from SOGETI (1995), but these could

TABLE V

Range of metal concentrations recorded in lagoon sediments (μgg^{-1} dry weight) by SOGETI (1995) and during islandwide survey of Mauritius (1999–2000).

Site	From SOGETI (1995) study Pointe aux Sables ($n = 20$, see Table I)		From 1999–2000 study Pointe aux Sables ($n = 5$)	
Metal	Concentration range (μgg^{-1})	Mean concentration	Concentration range (μgg^{-1})	Mean concentration
Copper	19.8–34.8	25.78 ± 4.46	23.5–48.2	35.8 ± 9.6
Chromium	26.7–34.7	30 ± 3.48	23.6–61.3	40 ± 16.1
Lead	16.9–47.8	28.18 ± 7.03	11.1–45.6	29.2 ± 13.4
Zinc	125–736	360.35 ± 170.67	397–661	491.2 ± 111.8
	From all measurements ($n = 22$, see table II)		From 20 sites around Mauritius (n = 51)	
Copper	19.8–47.7	26.68 ± 6.34	0.66–93.38 [a]	19.74 ± 18.99
Chromium	26.7–84	41.57 ± 21.85	3.28–91.39 [b]	22.57 ± 22.31
Lead	16.9–47.8	28.38 ± 7.13	2.71–98.1 [c]	26.69 ± 24.09
Zinc	118–736	339.05 ± 176.39	9.85–661	138.82 ± 191.27
Cadmium	na	na	0.03–55.01 [d]	8.21 ± 15.56
Tin	na	na	2.28–65.53 [e]	27.77 ± 17.01

na: not available.

Sites of highest metal accumulation: a: Poudre d'Or (NE); b: Ile d'Ambre (NE); c, d, e: Pointe Moyenne (W).

be due to the different sampling protocols used in the two studies. Whereas SOGETI (1995) collected the 20 samples from spots (or stations) along 4 transects throughout the lagoon (see Figure 2) on a single occasion, during the 1999–2000 study the 5 samples (4 revisits) were taken from one specific area in the middle of the lagoon (between SOGETI Transects TR3 and TR4) on 5 different occasions.

(ii) Analysis of the 51 samples from the 20 sites surveyed around Mauritius during 1999–2000 generated results with wider concentration ranges than the 22 samples analysed by SOGETI (1995), pointing to the existence of other sites around Mauritius having higher contamination than at Pointe aux Sables. The combined results from these two studies indicated the highest accumulations of the metals in the decreasing order: Zn: 736 μgg^{-1}, Pb: 98.1 μgg^{-1}, Cu: 93.38 μgg^{-1}, Cr: 91.39 μgg^{-1}, Sn: 65.53 μgg^{-1}, and Cd: 55.01 μgg^{-1}. The sites with highest metal accumulation (see Table V) were identified as follows: Poudre d'Or (NE, presence of a metal scrapyard) with 93.38 μgg^{-1} of Cu, Ile d'Ambre (NE, receives effluent discharge from a dyehouse) with 91.39 μgg^{-1} of Cr, and particularly Pointe Moyenne (W, recipient of raw sewage from the district of Plaine Wilhems with 25% of the total population) with 98.1 μgg^{-1} of Pb, 55.01 μgg^{-1} of Cd, and 65.53 μgg^{-1} of Sn.

TABLE VI

Average concentrations of metals in seawater (mgl^{-1}) at 20 sites around Mauritius, 1999–2000

Acceptable limit	Cadmium 0.02 (mgl^{-1})	Copper 0.05 (mgl^{-1})	Lead 0.05 (mgl^{-1})	Zinc 0.1 (mgl^{-1})$^{\psi}$	Chromium 0.05 (mgl^{-1})
Site (Figure 2)					
Poudre D'Or	0.012	0.025	0.031	0.242 ♣	0.29 ♣
Ile D'Ambre	0.041 ♣	0.083 ♣	0.051 ♣	0.256 ♣	0.26 ♣
Grand Gaube	0.045 ♣	0.056 ♣	0.01	0.084	0.09 ♣
Cap Malheureux	0.018	0.038	0.016	0.082	0.11 ♣
Grand Baie	0.201 ♣	0.341 ♣	0.104 ♣	0.157 ♣	0.26 ♣
Mon Choisy	0.112 ♣	0.088 ♣	0.022	0.116 ♣	0.21 ♣
Trou aux Biches	0.067 ♣	0.075 ♣	0.013	0.109 ♣	0.18 ♣
Baie du Tombeau	0.133 ♣	0.189 ♣	0.153 ♣	0.189 ♣	0.35 ♣
Bain des Dames	0.074 ♣	0.331 ♣	0.169 ♣	0.312 ♣	0.41 ♣
Pointe aux Sables	0.19 ♣	0.352 ♣	0.192 ♣	0.303 ♣	0.31 ♣
Albion	0.023 ♣	0.052 ♣	0.066 ♣	0.091	0.23 ♣
Pointe Moyenne	0.323 ♣	0.211 ♣	0.247 ♣	0.249 ♣	0.38 ♣
Flic en Flacq	0.019	0.018	0.01	0.126 ♣	0.12 ♣
Le Morne	0.027 ♣	0.072 ♣	0.062 ♣	0.099	0.09 ♣
St Felix	0.01	0.023	0.016	0.01	0.02
Palmar	0.012	0.018	0.01	0.012	0.02
Belle Mare	0.018	0.033	0.012	0.069	0.041
Poste de Flacq	0.019	0.03	0.019	0.065	0.043
Poste la Fayette	0.01	0.01	0.01	0.016	0.024
Pointe des Lascars	0.015	0.028	0.029	0.061	0.037
Range/Mean	0.01 − 0.232	0.01 − 0.352	0.01 − 0.247	0.01 − 0.312	0.02 − 0.41
	0.063 ± 0.079	0.099 ± 0.118	0.057 ± 0.073	0.132 ± 0.095	0.189 ± 0.119

♣ : denotes values exceeding guidelines applicable in Mauritius.
ψ : APHA *et al*. (1994).

4.2. Contaminant Metals in Seawater

4.2.1. *Results from Islandwide (1999–2000) Study*

The average concentrations of the 5 metals (Cd, Cu, Cr, Pb, Zn) measured at the 20 sites around Mauritius and their recommended guidelines in seawater are given in Table VI. The acceptable limits of all five metals were exceeded at several sites but not at those in the south and east. Contamination would appear to be generally higher along the coasts of the northern half of Mauritius and was particularly severe around the harbour of Port Louis, which is surrounded by an industrial zone in the sector between Baie du Tombeau in the north to Pointe Moyenne in the south. Considering the islandwide data, the computed mean values of all five metals were above their respective recommended limits, although sites in the east and south of the island had low contamination. Concentrations of all metals at Le Morne (south west) were also generally higher than the recommended guidelines despite the absence of industrial discharges nearby. However, freshwater inputs into the lagoon via rivers and underground seepages are quite substantial.

4.2.2. *Results from 2003 study of the sewage-impacted coast*
The average concentrations of the metals showed wider variation ranges at low water (see Table VII). Some distinct trends in metal distribution were: (1) Transects A and B generally had the highest concentrations, slowly declining in the direction of the control Transect H, (2) for transects from A to D, all metal concentrations increased from the shore towards the reef, but for transects from F to H the reverse was true, and (3) the control transect H had concentrations around the mid end of the distribution, which nearly in all cases were above the respective acceptable limits, an indication of the lagoon water around Mauritius being the recipient of significant amounts of metals from other sources than only sewage or industrial discharges.

In terms of the actual concentrations recorded from the various sites, the 5 trace metals could be conveniently grouped into two main categories: (1) Cr and Pb exceeded the recommended limit of 0.05 mgl^{-1} at most of the sites during low water. (2) Cd, Cu and Zn, with recommended limits of 0.02 mgl^{-1}, 0.05 mgl^{-1} and 0.1 mgl^{-1}, respectively, occurred at much higher concentrations than Cr and Pb values. Cu and Cd would be considered as the most available metals in the sewage impacted seawater of the survey area. However, considering the recommended limit of Cd, it would be considered as the most abundant and possibly of most concern amongst the metals investigated in this study.

4.3. CONTAMINANT METALS IN MARINE BIOTA FROM ISLANDWIDE (1999–2000) STUDY

Examination of the various data sets above illustrates that metal contamination of both the marine sediment and seawater can be high, namely at certain hotspots on the coast. Table VIII summarises the most essential results from biota analysis, presenting the marine plant and animal species which accumulated the highest concentrations of the metals alongside the values recorded in samples of sediment and seawater from their respective sites of collection. The most accumulated metal was Zn by *Isognomon isognomon* (563.1 μgg^{-1}) at Poudre d'Or (NE) and by *Enteromorpha ramulosa* (261 μgg^{-1}) at Bain des Dames (NW). At these sites Zn levels were also high in seawater (0.242 and 0.312 mgl^{-1}, respectively) as well as in the sediment (185.9 and 541.3 μgg^{-1}, respectively). At the clean sites e.g. St Felix (S) and Palmar (E) low levels of Zn were present in seawater (i.e. 0.01 mgl^{-1} and 0.012 mgl^{-1}, respectively, see Table VI) as well as in the sediment (i.e. 17.4 μgg^{-1} and 32.3 μgg^{-1}, respectively). *E. ramulosa* accumulated only 0.16 μgg^{-1} of Zn from St Felix and 0.42 μgg^{-1} from Trou aux Biches (NW, clean site). *I. isog nomon* also accumulated low levels of Zn from Palmar (46 μgg^{-1}) and Belle Mare (66 μgg^{-1}) on the east coast.

TABLE VII

Average concentrations of metals in seawater (mgl^{-1}) at high and low tides along the sewage-impacted coast, December 2003

Metal Guideline	Cd 0.02 (mgl^{-1})		Cu 0.05 (mgl^{-1})		Pb 0.05 (mgl^{-1})		Cr 0.05 (mgl^{-1})		Zn 0.1 (mgl^{-1}) $^{\psi}$	
Station	HW	LW	HW	LW	HW	LW	HW	LW	HW	LW
A1	0.271	0.288	0.193	0.257	0.088	0.108	0.055	0.058	0.198	0.21
A2	0.281	0.298	0.252	0.302	0.092	0.099	0.059	0.078	0.208	0.23
A3	0.303	0.312	0.273	0.341	0.109	0.128	0.097	0.102	0.225	0.235
A4	0.312	0.329	0.351	0.438	0.125	0.132	0.107	0.115	0.236	0.251
B1	0.229	0.245	0.308	0.369	0.077	0.092	0.075	0.086	0.193	0.199
B2	0.275	0.288	0.358	0.426	0.082	0.106	0.099	0.105	0.206	0.223
B3	0.281	0.301	0.375	0.431	0.103	0.124	0.108	0.119	0.218	0.233
B4	0.298	0.32	0.395	0.454	0.119	0.138	0.116	0.123	0.228	0.259
C1	0.196	0.222	0.203	0.243	0.063	0.081	0.044†	0.063	0.173	0.177
C2	0.218	0.232	0.223	0.267	0.076	0.095	0.051	0.073	0.187	0.196
C3	0.252	0.261	0.268	0.308	0.081	0.099	0.088	0.092	0.187	0.205
C4	0.283	0.296	0.277	0.318	0.094	0.108	0.097	0.121	0.201	0.218
D1	0.258	0.265	0.213	0.255	0.062	0.078	0.055	0.066	0.203	0.215
D2	0.264	0.268	0.245	0.294	0.074	0.087	0.06	0.073	0.217	0.224
D3	0.267	0.268	0.26	0.299	0.085	0.099	0.075	0.094	0.218	0.231
E1	0.24	0.26	0.208	0.239	0.084	0.095	0.085	0.099	0.209	0.22
F1	0.231	0.248	0.258	0.261	0.065	0.077	0.059	0.066	0.171	0.188
F2	0.217	0.225	0.247	0.296	0.059	0.085	0.044†	0.048†	0.166	0.175
F3	0.204	0.219	0.234	0.299	0.048	0.064	0.04†	0.041†	0.17	0.17
F4	0.196	0.2	0.218	0.296	0.05†	0.06	0.037†	0.038†	0.166	0.168
G1	0.216	0.228	0.177	0.212	0.068	0.072	0.065	0.075	0.164	0.172
G2	0.203	0.215	0.176	0.21	0.064	0.07	0.058	0.063	0.157	0.17
G3	0.199	0.209	0.162	0.186	0.058	0.063	0.044†	0.059	0.164	0.162
G4	0.192	0.198	0.158	0.181	0.052	0.061	0.045†	0.061	0.16	0.162
H1	0.188	0.2	0.104	0.124	0.051	0.055	0.06	0.068	0.147	0.15
H2	0.169	0.176	0.104	0.109	0.054	0.058	0.058	0.064	0.151	0.145
H3	0.158	0.17	0.099	0.108	0.048†	0.05†	0.044†	0.045†	0.14	0.145
H4	0.161	0.172	0.089	0.098	0.047†	0.048†	0.045†	0.045†	0.152	0.15
Minimum	0.158	0.17	0.089	0.098	0.047	0.048	0.037	0.038	0.14	0.145
Maximum	0.312	0.329	0.395	0.454	0.125	0.138	0.116	0.123	0.236	0.259
Mean	0.234	0.247	0.230	0.272	0.074	0.087	0.067	0.076	0.186	0.196
Std Dev	0.045	0.046	0.082	0.099	0.022	0.025	0.024	0.025	0.028	0.034

HW: high water; LW: low water; †: denotes values not exceeding guidelines applicable in Mauritius.
ψ: APHA *et al*. (1994)

Cu was also accumulated to high levels e.g. 154.9 μgg^{-1} by *Crassostrea cucullatta* at Poudre d'Or, and 23.3 μgg^{-1} by *E. ramulosa* at Bain des Dames, where levels in both seawater and sediment were again very high compared to the above two clean sites (i.e. St Felix and Palmar). The following were accumulated to lesser extents: Sn (139 μgg^{-1} by *Ulva lactuca* at Bain des Dames), Pb (44.2 μgg^{-1}

TABLE VIII

Highest metal concentrations recorded in nearshore marine biota (μgg^{-1}) alongside concentrations in sediment (μgg^{-1}) and seawater (mgl^{-1}) collected from their respective sites, 1999–2000. (BCF = highest bioconcentration factor)

Species with highest metal concentration	Site	Cadmium Tissue (μgg^{-1}) range and mean	Cadmium Sediment (μgg^{-1}) range and mean	Cadmium Water (mgl^{-1}) mean	Copper Tissue (μgg^{-1}) range and mean	Copper Sediment (μgg^{-1}) range and mean	Copper Water (mgl^{-1}) mean
Ulva lactuca BCF value = 42	Pointe aux Sables (NW)	0.19 – 8.12 3.13 ± 3.24	20.06 – 53.25 33.33 ± 11.64	0.19			
Morula granulata BCF value = 24	Pointe aux Sables (NW)	0.34 – 4.59 1.46 ± 2.41	20.06 – 53.25 33.33 ± 11.64	0.19			
Enteromorpha ramulosa BCF value = 70	Bain des Dames (NW)				3.37 – 23.3 9.09 ± 8.2	18.11 – 62.6 36.04 ± 23.47	0.331
Crassostrea cuculatta BCF value = 620	Poudre d'Or (NE)				82.3 – 154.9 92.85 ± 51.13	69.2– 93.4 79.8 ± 17.09	0.25
		Lead			Chromium		
Enteromorpha ramulosa BCF value = 262	Bain des Dames (NW)	1.65 – 44.2 11.3 ± 18.4	28.5 – 38.18 32.63 ± 4.99	0.169			
Pinna muricata BCF value = 267	Ile d'Ambre (NE)	6.44 – 13.6 9.97 ± 4.99	70.04 – 80.02 75.03 ± 7.06	0.051			
Enteromorpha ramulosa BCF value = 104	Pointe des Lascar (NE)				0.61 – 19.8 9.15 ± 7.85	8.16 – 12.17 10.13 ± 2.03	0.19
Morula granulata BCF value = 190	Mon Choisy (NW)				25.6 – 39.9 32.75 ± 10.11	9.52 – 14.06 11.68 ± 1.74	0.21
		Zinc			Tin		
Enteromorpha ramulosa BCF value = 836	Bain des Dames (NW)	32.1 – 261 171 ± 84	189.4 – 541.3 374.8 ± 176.9	0.312			
Isognomon isognomon BCF value = 2326	Poudre d'Or (NE)	166.6 – 563.1 335.7 ± 204.6	132.6 – 185.9 165.87 ± 25.49	0.242			
Ulva lactuca HCF value = 421	Bain des Dames (NW)				6.83 – 139 57.6 ± 36	37.1 – 59.5 46.34 ± 11.7	0.033
Echinometra mathaei BCF value = 1384	Flic en Flac (W)				10–18 12 ± 3.7	21.3 – 34.1 27.7 ± 6.4	0.013

by *E. ramulosa* at Bain des Dames), Cr (39.9 μgg^{-1} by *Morula granulata* at Mon Choisy) and Cd (8.12 μgg^{-1} by *U. lactuca* at Pointe aux Sables). The above demonstrate that these plant and animal species have high bioconcentration potential and could be employed as bioindicators for the metals in monitoring and environmental state-of-health studies. The green alga *E. ramulosa* would be suitable for all the metals studied, except maybe for Sn. However, *U. lactuca* would be more appropriate for this metal as it could also be suitable for Cd. *E. ramulosa* with a concentration range of 0.16–5.48 μgg^{-1} (mean = 2.02 ± 0.98 μgg^{-1}) would also be suitable for Cd. The most relevant animals to serve as potential bioindicators would appear to be the bivalve species *Crassostrea cucullata* (e.g. for Cu), *Pinna muricata* (e.g. for Pb) and *Isognomon isognomon* (e.g. for Zn). The list of coastal sites where accumulation by these organisms was highest corresponded to those sites with highest metal concentrations in seawater and sediment. These hot spots occurred namely on the western and north eastern coasts of Mauritius, receiving either untreated sewage and/or discharges of industrial effluents.

5. Summary and Discussion

5.1. Metals in seawater

Metal concentrations in seawater were recorded at 20 sites around the island (1999–2000) and 28 stations along 8 transects (Figure 4) between Pointe aux Sables and Le Morne (2003) on the west coast, and were compared with applicable guidelines in Mauritius. The computed mean values of Cd, Cu, Cr, Pb and Zn in the first study were above their respective recommended values (see Table VI). The sites with higher water contamination corresponded to those with higher sediment contamination (e.g. Bain des Dames, Pointe aux Sables and Pointe Moyenne), all receiving untreated sewage and/or industrial effluents along the western coast. Le Morne in the southwest also showed high contamination although major waste discharges did not occur nearby as is the case around the harbour of Port Louis. Over 50% of the sites around Mauritius had metal concentrations above their recommended levels (see Table VI). Metals abundance was in the decreasing order Zn > Cr > Cu > Pb > Cd.

The 2003 study of the sewage impacted western coast between Pointe aux Sables and Le Morne indicated metal abundance in the decreasing order Cu > Cd > Zn > Pb > Cr. Contamination decreased away from the outfall, towards the shoreline area along transects from A to D (a pattern of water contamination similar to that of sediment contamination observed in the data of SOGETI,1995), and towards the reef along transects from F to H further away from sewage inputs. In terms of abundance, the 5 metals could be conveniently grouped in 2 categories: Cr and Pb, and Cd, Cu and Zn. Concentrations of the latter category were up to 4 times higher than the first. The backreef stations of transects from F to H had concentrations of Cr and Pb below the recommended limit of 0.05 mgl^{-1}, but the acceptable limits for the other category were exceeded everywhere. The recommended limits for Cd, Cu and Zn were exceeded in all the samples and those for Pb and Cr in over 50% of the samples. These two studies do point to metal contamination around Mauritius being a real issue, especially at the hotspots which necessitate a close monitoring.

That concentrations at Le Morne were also above the recommended limits would imply abundant metal inputs from other terrigenous sources than only sewage or industrial discharges. In fact, this lagoon receives substantial freshwater inflow via two rivers and underground seepages (Muller, 1991). Rigorous studies on the pattern of contamination of the major freshwater courses could establish other sources of metal input into the Mauritian lagoons in addition to the deliberate waste discharges at the hotspots idendified above. Also, knowledge of metal loadings into the lagoons during the wet season, severe floods and droughts as well as cyclonic episodes would help model effectively the natural versus anthropogenic contamination of the coastal waters.

5.2. Metals in marine sediment

Background contamination by metals of the coastal surficial sediment of Mauritius was evaluated by comparing values reported in literature with data reported from SOGETI study (1995) and from data of the 1999–2000 survey. Metal concentrations from Pointe aux Sables lagoon presented by SOGETI (1995) were higher than values reported from coastal sites in several other countries (e.g. Table II). Although sediments are not all comparable, and concentrations in them are not comparable either for that reason, the comparison is used here only to suggest a high input of contaminant metals into the coastal environment of Mauritius. The main source of contamination would not only be the outfall discharge but also the southward flowing water from the harbour area (Figure 4) where the freshwater systems of direct influence include the G.R.N.W., St. Louis River and several streams and rivulets. Direct discharges of untreated effluent and overflows from sewer networks into these water courses occur frequently and eventually reach the sea. Textile related industries produce approximately 90% of the industrial wastewater in the area, and the remaining is generated by food processing (canning, ethanol distilling and bottling), various chemical manufacture (e.g. soap, detergent, paint), laundries, battery making, galvanizing and electroplating plants, and light engineering (Black and Veatch International, 1997). Slightly higher values were obtained for the same lagoon during the 1999–2000 survey (e.g. Table V). Metal loadings to the lagoon sediment would thus be continuous and depend on the intensity of industrial activity in the area. The worst contamination from the industrial effluents would however be expected during spring tide low water conditions as indicated by the higher metal concentrations recorded in seawater at low tide during the 2003 study of the sewage-impacted coast. Whether terrigenous contribution of metallic contamination to the lagoon sediment is seasonal, being higher during winter (low precipitation) as reported for nearby St. Louis River sediment (Ramessur and Ramjeawon, 2002), has yet to be investigated.

It was argued that the higher results observed during the 1999–2000 survey could be due to the different sampling protocols, but whether an increasing trend in contamination is also real, especially in terms of environmental impact, could be demonstrated by the application of sediment quality guidelines (SQG). Unfortunately such guidelines were not used in this study because they do not exist in Mauritius, but standard procedures using the porewater toxicity test approach for evaluating the quality of marine and estuarine sediments have been demonstrated to be amenable for use with a wide variety of test species including embryo/larval stages of molluscs, polychaetes, crustaceans, echinoderms, and fish (Carr, 1997). Also, manipulative field-experimental studies of the effects of contaminant metals

(Morrisey *et al.*, 1995) could lead to the development of sediment quality criteria (SQC). Future application of such SQG and SQC would be useful to gauge the effectiveness of control measures if source reduction became widespread resulting in a decrease in the flux of metals to the sea, such as ending of raw sewage discharge, improvements in wastewater handling and sewage treatment, recycling and recovery, closing or moving of companies, and diminishing use of lead in gasoline. Guidelines and criteria established using such procedures would be a vital tool for assessment and monitoring of sediment quality to understand what kind of risk the presence of contaminant metals in sediment may pose to human health, fisheries, ecosystem sustainability, or recreational use of an area. From the above studies metal abundace in the coastal sediment of Mauritius was in the decreasing order Zn > Mn > Pb > Cu > Cr > Sn > Cd. The hotspots of sediment contamination for each metal were identified as being directly linked to a particular type of coastal waste disposal, but the environmental impact associated with the high levels of the metals have not been studied. The findings from these studies clearly point to the need for a close monitoring of metal contamination of the marine sediment at these hotspots. Uunleaded petrol has been introduced since 2004, an islandwide sewerage system has been projected and is being initiated, recently many textile manufacturing enterprises have closed and relocated elsewhere under the pressure of globalization, major radical transformations are expected in the sugar sector geared by policy reforms in the EU and tourism development will intensify further. Whether such developments will translate into a real phasedown of heavy metals into the coastal environment will have to be evaluated using established guidelines and criteria.

5.3. Bioindicators

Many marine organisms widely used as biomonitors accumulate heavy metals to very high tissue and body concentrations. The bioavailable metal can be easily measured and is not liable to contamination. In the 1999–2000 survey in Mauritius analysis of tissues of organisms permitted idendification of potential bioindicators (see Table VIII) for use in monitoring and environmental state-of-health studies. This was based on the highest concentrations of the metals accumulated from seawater and is reflected in the BFC values, which essentially indicate the bioconcentrating capability of organisms with respect to their surrounding environment. Bioconcentration by these organisms was high at the hotspots and low at the clean sites, thus displaying optimal characteristics for use as biomonitors. The organisms identified as potential biomonitors occur commonly in the littoral of Mauritius and good support in their favour as candidates can also be gained from published literature on the subject.

Species of *Ulva* and *Enteromorpha* have particular potential for biomonitoring (Rainbow, 1993). *U. lactuca* was used successfully in a comparative study of four sites in Hong Kong waters (Wong *et al.*, 1982), and in a study on heavy metals it was found to be a good metal accumulator (BFC values of 810 for Cr, 540 for Ni and 280 for Co) in natural coastal waters of Egypt (El-Nady and Atta, 1996). Concentration factors of 1500 (Zn), 900 (Mn), 800 (Cu) and 310 (Cd) for *U. lactuca,* and 1200 (Zn), 900 (Mn), 700 (Cu) and 340 (Cd) for *Enteromorpha clathrata* were reported from Aquaba, Jordan (Wahbeh, 1985). *U. lactuca* has been used widely as a heavy metal indicator (e.g. Fe, Mn, Pb, Zn, Cu, Cd) and it was successfully utilized in Thermaikos Gulf, Greece to assess these metals (Haritonidis and Malea, 1999). A high potential was reported for *Enteromorpha* species for use as bioindicator of Pb, Cu and Cd from studies in Northwest Portugal (Fernanda Leal *et al*., 1997). *Enteromorpha crinita* was successfully employed as a biomonitor in Hong Kong waters (Wong *et al*., 1978) and use of *Enteromorpha* species was advocated in temperate coastal waters (Say *et al*., 1986). In this study, whilst exhibiting generally high BCF values at the hot spots, both *U. lactuca* and *E. ramulosa* accumulated only very low levels of the metals at the cleaner sites. Their use would thus be very relevant in Mauritius, and especially so because both often occur as a thick cover on shore rocks or as putrefying heaps of dislodged algae with unpleasant smells on sandy beaches where they are eye-catching signs of eutrophication and severe littoral degradation (Daby *et al*., 2002; WMC, 2004).

The calcareous skeletons of sea urchins can concentrate metallic elements from seawater by up to several thousand times and two species (*Paracentotus lividus* and *Arbacia lixula*) were reported with high capacity of concentration of heavy metals in Portman Bay, Spain (Auernheimer and Chinchon, 1992). The urchins showed BCF values of up to 3112 for Mn, 8800 for Fe, 1616 for Pb and 278 for Zn. *Echinometra mathaei* occurs abundantly around Mauritius and showed a high BCF value of 1384 for Sn, thus quite suitable as an indicator. Bioconcentrations of heavy metals in tissues, gonads and fluids of sea urchins were investigated in UK, Ireland and Egypt and the edible species *Paracentrotus lividus* was proposed as a bioindicator of local heavy metals (Mostafa and Collins, 1995). Higher concentrations of heavy metals in marine gastropods were reported from polluted water compared to clean water of the Mediterranean (Nott and Nicolaidou, 1989). For example, *Cerithium vulgatum*, *Monodonta articulata* and *Murex trunculus* accumulated the following on a dry weight basis: 15728, 107 and 1899 μgg^{-1} of Zn, and 165, 206 and 14 μgg^{-1} of Cr (polluted water) compared to 3510, 84 and 512 μgg^{-1} of Zn, and 49, 18 and 0.6 μgg^{-1} of Cr (clean water), respectively. Other gastropods which have been studied as indicators include *Nucella lapillus* and *Littorina littorea* in Ireland (Minchin *et al*., 1997) and *Thais clavigera* in Japan (Rainbow and Phillips, 1993). Use of the gastropod *Morula granulata* as bioindicator of cadmium in Mauritius is however not recommended not only because of the low BCF value (see Table VIII), but also toxicity tests on this organism from the east coast of India indicated low tolerance to heavy metals such as Cu, Cd, Zn and Hg (Uma Devi, 1997), hence not suitable as a bioindicator. Use of bivalve molluscs as biomonitors of metals (Martincic, 1986) is now widespread (e.g. the Worldwide Mussel Watch Studies). Common examples from recent literature include species of *Mytilus*, *Perna*, *Crassostrea*, *Saccostrea*, *Ostrea*, and others such as *Septifer virgatus*, *Trichomya hirsuta* (Saiz-Salinas, 1996; Rainbow, 1995; Chu *et al*., 1990; Cantillo, 1998). The bivalve species suggested for use in Mauritius are *Crassostrea cuculatta* for Cu (BCF value of 620) and *Isognomon isognomon* for Zn (BCF value of 2326), which are very common on some rocky shores. The animal species recommended for use as bioindicators in Mauritius also accumulated only very low levels of the metals at the cleaner sites.

This study aimed principally to identify the best bioindicators among a certain number of plant and animal species based solely on the intensity of bioaccumulation, but does not provide any clue as to the health and stability of the populations or communities of the test organisms used (bivalves, gastropods, sea urchin). Assessment of ecological dysfunction and ecosystem perturbation through responses of the biocoenose is possible, but this would require a rigorous sampling and analysis, which was beyond the scope of the present work. Also, corals are an important omission in this work because toxic metals are bioaccumulated in the newly formed layers of the calcareous exoskeletons of madrepores (e.g. Brown and Holley, 1982; Schneider and Smith, 1982; Glynn *et al*., 1989), which can constitute an efficient indicator for monitoring. A separate study on metals in corals is highly commendable, being given the wide variety of species and their crucial ecological, economic and social significance to the Mauritian community.

6. Conclusion

Enhanced levels of contaminant metals were identified in water, sediment and biota, especially at hotspots linked to different sources and types of waste discharge around Mauritius. The general indication was one of an incessant increase in the accumulation of metals with development of anthropogenic activities, pointing towards a model of dynamic contamination of the coastal environment despite the much lower intensity of industrial than marine tourism development on the island. This inventory of present contamination levels will be useful for potential environmental remediation and ecosystem restoration at contaminated sites and provides a scientific basis for standards and protective measures for the coastal waters and sediments. Use of benthic biota (e.g. macro-algae and invertebrates), by reflecting the cumulative effects of pertubations over time, have the potential to offer a more effective method for measuring anthropogenic impacts than purely chemical measurements (e.g. water and sediment). The suite of biomonitors proposed in this study (and others to be identified) would allow identification of the different metal sources as well as provide an assessment of the magnitude of metal contamination in the coastal marine environment. It is advocated that this work constitutes a first step towards the pressing need to identify and establish widespread cosmopolitan biomonitors for such assessment within the longer-term perspectives of coastal zone management in Mauritius.

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