Sediments of Leschenault Inlet: a comparison with other estuaries in south-western Australia

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Abstract

This paper describes the properties of sediments from Leschenault Inlet, south-western Australia, and compares them with two other estuarine systems in the South West, the Swan-Canning and the Peel-Harvey. Surface sediments of Leschenault Inlet contained a large proportion of fine material, with a particle size finer than in Peel-Harvey sediments. Organic enrichment in surface sediments was higher than that in Peel Inlet, and comparable with part of the eutrophic Harvey Estuary. It was lower than central Harvey Estuary and the Swan-Canning Estuary. Sediments contained a substantial proportion of apatite P, distinctly higher than in Peel-Harvey and Swan-Canning. Concentrations of sediment total phosphorus were relatively low, but higher than in Peel Inlet. The rate of phosphorus release was low compared with the Peel-Harvey and the Swan-Canning.

Keywords: Leschenault Inlet, south-western Australia, estuary, sediments, nutrients.

Introduction

Leschenault Inlet (Fig 1) is located near Bunbury, 180 km south of Perth, Western Australia. It is a long, narrow, shallow (< 2 m) interdunal lagoon, approximately 11 km long and 2 km wide. The estuary is open to the Indian Ocean through a channel dredged in 1951.

The system is fed by two main rivers, the Collie and the Preston. The Collie, with a catchment of 3 500 km^2, is fed by the Brunswick, Wellesley and Lunenburgh Rivers from the east of the catchment. The Preston, with a catchment of 1 400 km^2, is fed by several tributaries; Ferguson River, Joshua Brook and Crooked Brook. Several dams on the two main rivers provide water for irrigation and domestic supply. Wellington Dam is on the Collie, south of Collie township, and the Glen Mervyn dam is on the upper reaches of the Preston.

The climate is Mediterranean with an annual rainfall of about 1000 mm, mainly concentrated (87%) between May and August. The average maximum temperature in winter in Bunbury is 16.8 °C (July), while in summer the average daily maximum is 27.6 °C and the average minimum is 15.1 °C. Easterly winds prevail in summer, but a strong south-west breeze occurs on most afternoons.

The Inlet has significant environmental and economic value to the region, and the waterway and its surrounds are a hub of recreational activity. It has safe, protected waters, most of which are freely navigable by small pleasure craft. Much of its popularity is due to its quality as a recreational fishing and crabbing area.

The Inlet has a diversity of ecologically-important habitats including seagrass beds, tidal mud, sand flats, salt marshes, fringing sedgelands, heathlands and *Melaleuca* woodland, with their associated biodiversity. It contains small remnant stands of the grey mangrove, *Avicennia marina*. The areas of aquatic vegetation and mangroves are nursery areas for fish and invertebrates, many of which are important to the recreational fishing industry.

The coastal plain catchment of Leschenault Inlet consists largely of sandy soils with low nutrient retention capacities (Anon 1983). Nevertheless the Inlet has been seen as a healthy, biologically-productive waterway with relatively little algal growth. There were no significant water quality problems revealed in the Collie River during monitoring in 1993-95. It has been considered one of few estuaries with a low risk of nutrient enrichment, according to the US EPA risk assessment model for estuarine eutrophication. However, the estuarine reaches of the Collie River have shown physio-chemical and biological signs of nutrient enrichment in recent years. Phytoplankton blooms of *Cryptomonas* sp and *Heterosigma akashiwo* occurred in the Collie River near its confluence with the Brunswick River in April and May 1994 (Anon 1995). There were high levels of plant biomass, comparable (on a unit area basis) with those of Peel-Harvey. Seagrass and brown algae are dominant, and appear not to be limited by nutrient availability (Lukatelich 1989; Hillman *et al.* 2000).

There are limited data on nutrient enrichment and water quality in the Inlet. Data from well-documented estuaries in south-western Australia suggest that excessive nutrient loads, and especially phosphorus and nitrogen from agricultural and urban catchments, can be a major threat to estuarine water quality and ecological health. Compared with the rural catchment, nutrient loads from the Bunbury urban area and from groundwater are relatively small. Nutrient loads entering the estuary vary from year to year corresponding to rainfall and stream flow, but it has been estimated that an annual average of about 51 tonnes of phosphorus and 610 tonnes of nitrogen enter the estuary though surface run-off from the rural catchment (Anon 1995).

Sediment is important in nutrient cycling in estuarine systems because it stores large amounts of nutrients, and may release them when the concentration in the overlying water is low (Thornton *et al.* 1995). In many cases sediment can be significant, either as a source or sink, adjusting nutrient concentrations in the water column, and so controlling primary production and the possibility of algal blooms. It is therefore important to understand the sediment properties of the estuary, and especially physico-chemical properties of the surface sediment. These matters

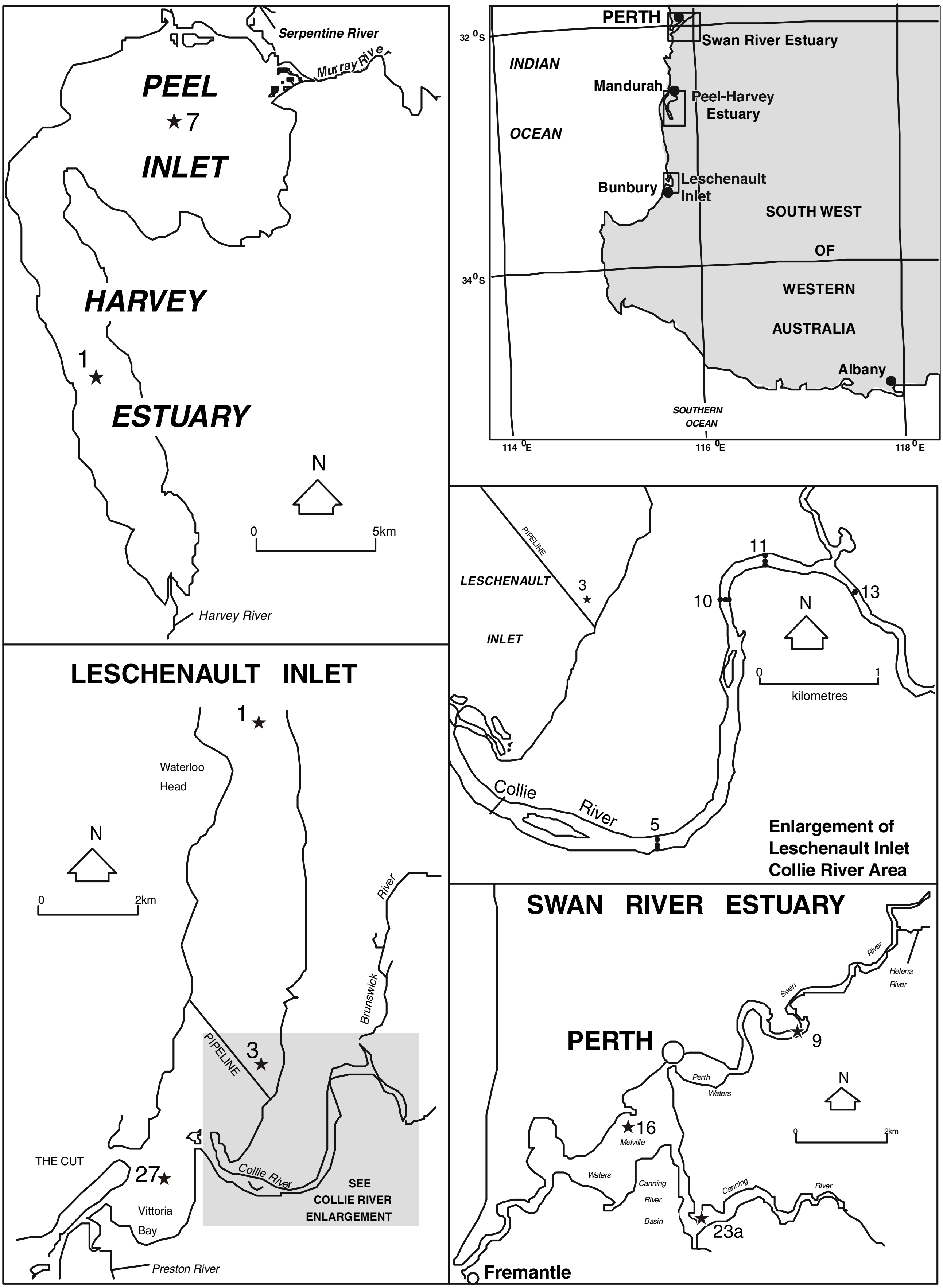

Figure 1. Sampling sites in Leschenault Inlet, Peel-Harvey, and Swan-Canning Estuarine Systems.

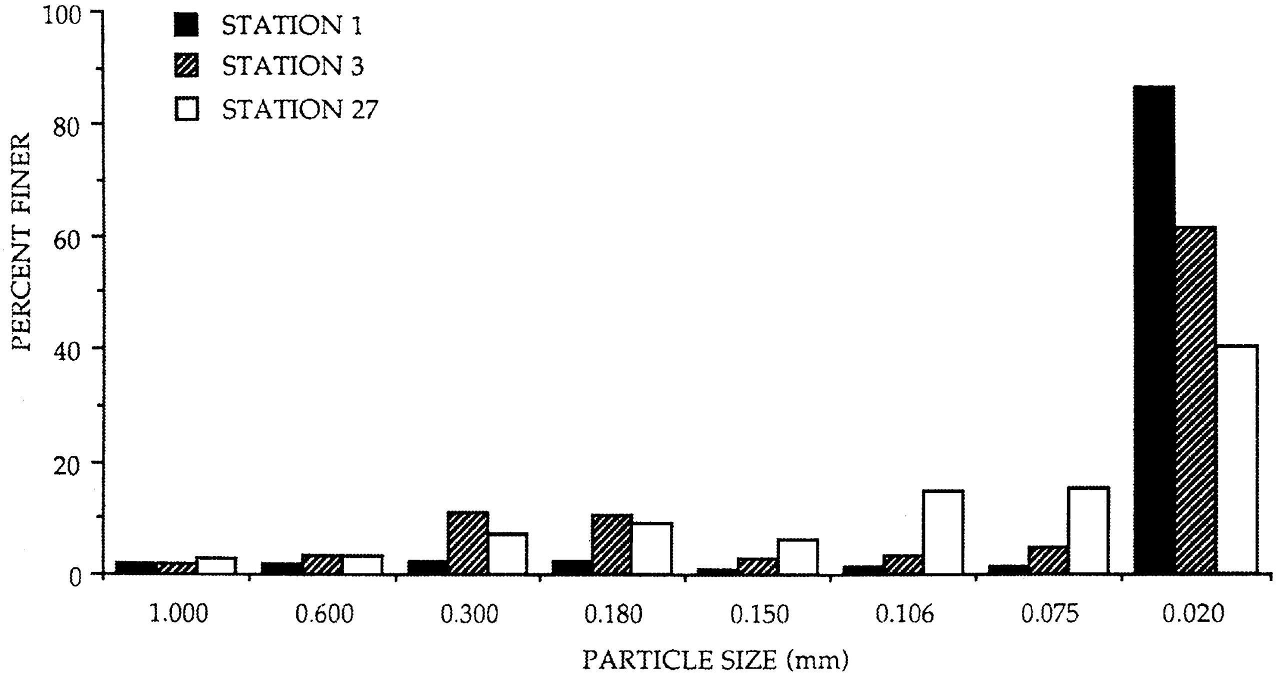

Figure 2. Particle size distribution for sediments from Leschenalut Inlet.

are addressed in this paper, which compares the sediments of Leschenault Inlet with those of others, more intensively studied estuarine systems in south-west Australia, the Swan-Canning and Peel-Harvey.

Materials and Methods

Sampling

Sediment monitoring commenced in September 1988 and continued until July 1990. Samples were taken for physical and chemical analysis from 11 sites in Collie River in July 1990, and monthly at 3 sites in Leschenault Inlet, 5 in Peel Inlet, 7 in Harvey Estuary and 6 in Swan-Canning Estuary (Fig 1).

Samples were collected from the top few centimeters by SCUBA diving, returned to the laboratory and stored overnight at 4 °C. They were dried (105 °C), ground and stored until analysis. To obtain mixed samples of surface sediment from a larger area at each site, ten sediment cores were taken from each site by pressing a perspex coring tube gently into the sediment. The upper 5 mm of sediment was extruded from the cores, placed in a bucket and well mixed. Sub-samples were stored on ice in the field and at 4 °C in the laboratory. During toxic *Nodularia* blooms in the Peel-Harvey Estuary between November and February it was not safe to dive. On three such occasions cores were therefore collected remotely using a perspex cylinder attached to a long pole operated from the boat. On these occasions only one core was taken at each site.

Intact cores were collected by SCUBA diving for metabolic work in the laboratory. A perspex cylinder, 50 cm by 9.5 cm (internal diameter), was gently pressed approximately 15 cm into the sediment. The intact sediment and cylinder were removed with the associated water column, taking care not to disturb the sediment/water interface, sealed with rubber bungs, transported to the laboratory, covered with black polythene, and incubated at 20 °C. Similar intact cores were collected from site 7 in Peel Inlet, site 1 in Harvey Estuary, sites 1, 3 and 27 in Leschenault Inlet and sites 9, 16 and 23A in the Swan-Canning Estuary.

Data recording and analysis

Wet to dry ratio (W/D) was determined by drying a known weight of wet sediment [water content = 1-(D/W)]. Percentage organic matter was determined by loss on ignition (550 °C, 1 hr).

Additional sediment samples were collected for particle size analysis. These were dried overnight (105-110 °C), weighed, and immersed in an aqueous solution of the dispersant sodium hexametaphosphate (2 g L^{-1}). The samples were periodically agitated until all sediment was dispersed. The suspension was passed through a nest of sieves which divided the particles into size classes: < 75 µm, 75-150 µm, 150-355 µm, 355-710 µm and > 710 µm. These fractions were dried, weighed and the cumulative frequency of particle size classes calculated according to Buller & McManus (1979).

Total phosphorus was determined by digesting 1 g of dried sediment with concentrated perchloric acid. Nitric acid was added first to digest volatile organic substances which may form explosive substances in the presence of perchloric acid. The released phosphate, as soluble reactive phosphorus (SRP), was measured colorimetrically with the acid molybdate/ascorbic acid reagent described by Strickland & Parsons (1972) and measured with a Varian 634 or DMS 90 spectrophotometer.

The method for phosphorus fractionation was similar to that of Williams *et al.* (1976), but without citrate-dithionite-bicarbonate (CDB) extraction. Sediment $CaCO_3$,

Table 1. Particle size distribution of sediments from Leschenault Inlet and Collie River*. See Fig 1 for site locations.

Location	Site	Q1	Median	Q3	QD	Skewness
Leschenault Inlet	1	5.8	6.0	6.2	0.2	0.00
	3	2.6	5.9	6.2	1.8	0.01
	27	2.9	4.4	6.0	1.55	-0.29
Collie River	5 (North)	3.8	4.1	6.6	1.4	-0.01
	5 (South)	0.7	1.8	5.2	2.2	0.03
	5 (Centre)	0.3	0.5	4.5	2.1	-0.28
	10 (West)	2.2	4.6	6.3	2.0	0.07
	10 (East)	1.3	4.0	6.1	2.4	0.15
	10 (Centre)	3.6	5.0	6.5	1.4	0.03
	11 (North)	0.6	1.3	2.5	0.9	0.02
	11 (South)	0.7	3.0	5.8	2.5	0.19
	11 (Centre)	1.1	2.4	5.5	2.2	0.05

Footnote: Q1 = 1st quartile (first 25% cumulative frequency as weight percentage), Median (first 50% of cumulative frequency as weight percentage), Q3 = 3rd quartile (75% of cumulative frequency as weight percentage), QD (quartile deviation); and skewness of distribution frequency.

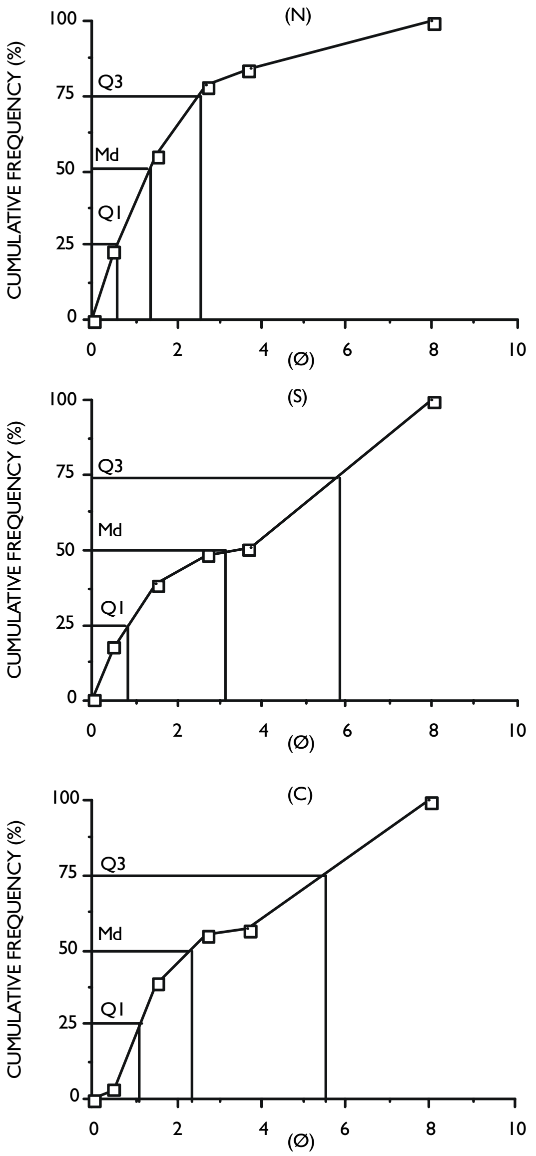

Figure 3. Cumulative weight frequency and particle diameter (Ø) for sediments from Collie River Site 11, north (N); south (S); and centre (C). Ø = - $\log_2$ (particle size mm).

Ca, Fe and Al content were analysed by the Chemistry Centre of Western Australia. Ammonia was measured by the isocyanurate method (Dal Pont *et al.* 1974).

Phosphate release rates were determined by measuring concentrations of total and soluble reactive phosphorus in the water column above the sediment in intact cores collected monthly from each estuary. Samples were withdrawn from each core on five occasions over approximately 10 days. On each occasion measurements were made of pH (Beckman Model 021), temperature, dissolved oxygen (Xertex Delta Model 4010 or Yeokal) and redox potential (Orion Model 20 meter with platinum and reference electrodes).

Results and Discussion

Sediment particle size

Particle size fractions finer than 75 µm ranged from 40.4 to 87.0% at the three sites in Leschenault Inlet. Most particles were less than 20 µm, particularly at site 1 (Fig 2).

Sediments from sites 3 and 27 had a relatively higher percentage of coarse particles and a wider range of values, reflected in the variation of the median particle size, and the quartile deviation, suggesting these sediments were poorly sorted (Table 1). The skewness values for sediments from sites 1 and 3 were near zero but a value of -0.29 for site 27 sediments suggested that the cumulative frequency of sizes was skewed towards coarse particles. There was a wide variation in median particle size (MD) for sediments from Collie River (Table 1). The average MD (in Ø) from site 10 was significantly higher than other sites, reflecting a higher proportion of finer particles with distance from the point of discharge into the estuary.

The quartile deviation in particle size distribution ranged from 0.9 at site 11 (north) to 2.5 at site 11 (south), indicating a significant difference in the level of particle-sorting force in transects across the Collie River (Table 1). This can be attributed to changing velocity of the flow around river bends, across banks and in depressions on the river bed. Seasonal flooding of the Brunswick River, carrying a large volume of silty water, enters the Collie River about 500 m upstream of site 11. The merging of the two streams increases scouring of the riverbed downstream, and forms 'high energy' sites which favour only sedimentation of larger and coarser sediments; and some 'low energy' sites which favour sedimentation of finer particles. There would thus be significant differences in flow velocity and "energy" levels across the river, and the sediments would be poorly-sorted in some regions and well-sorted in others.

The particle size distributions of Collie River Site 11 are illustrated in Fig 3. The third quartile values were relatively high at all sites, with the exception of site 11 (north). This suggests that finer particles accumulated in most sampling areas of the river bed of the Collie River.

The skewness of particle size distribution indicates, in comparison to a sample considered completely mixed, the presence of size classes over- or under-represented. The skewness values varied significantly at all sites, a positive value indicating higher accumulation of finer particles, a negative value that the distribution was more on the coarse side, an effect of higher flow affecting the riverbed. The skewness therefore indicates the "energy level" of the deposition environment and the degree of the particle mixing (Sly 1978). There was little skewness in the distribution pattern at the centre and western side of site 10 and northern side of site 11; the distribution of particle size in these sediments was relatively symmetrical around the mean value.

W/D ratio and organic content

The wet to dry ratios (W/D) from sites 1 and 3 averaged from 2.11 to 3.08 (Table 2). The range was highest at site 3, near the middle of the inlet adjacent to the SCM pipeline. There was a greater depth gradient at this site. The water depth of the sites ranged from 0.5 m (site 1) to approximately 2.0 m (site 3).

Mean organic content was 8.6 to 12.1% (Table 2). Sediment organic content in Leschenault was higher than in Peel Inlet, comparable with some sites in Harvey Estuary, and clearly lower than in the Swan River. Distribution of sediment Al and Fe in these four estuaries followed the pattern of organic content. In Leschenault, concentrations were highest at site 1 and lowest at site 27, which was

Table 2. Physical and chemical properties of the sediments from Leschenault Inlet, Harvey Estuary, Peel Inlet and Swan-Canning Estuary.

Estuary	Site	W/D*		Organic matter (%)		$CaCO_3$ (%)	Al (%)	Fe (%)	Ca (%)
Leschenault Inlet	1	2.83	(2.79-3.97)	11.17	(9-8-15.2)	13.0	3.6	4.4	13.0
	3	3.08	(1.85-4.50)	12.08	(5.7-14.9)	8.0	3.4	4.0	2.5
	27	2.11	(1.72-3.41)	8.60	(3.9-15.6)	24.0	1.5	1.9	2.4
Harvey Estuary	1	4.88	(2.72-6.29)	17.72	(12.2-22.0)	9.0	6.0	3.8	2.9
	28	2.69	(2.20-3.56)	8.73	(1.0-11.9)	6.0	2.6	1.8	2.1
	29	3.55	(2.30-5.05)	10.84	(8.0-17.6)	35.0	4.2	2.6	14.4
	30	1.30	(1.28-1.58)	2.30	(1.0-3.5)	2.0	0.8	0.5	0.6
	31	2.21	(1.51-6.00)	5.38	(1.8-19.0)	3.0	1.0	0.6	1.0
	37	3.41	(1.73-6.25)	9.49	(3.0-18.4)	1.0	1.8	1.2	0.2
	P59	4.60	(3.14-5.65)	18.63	(11.7-22.0)	9.0	7.6	5.5	1.6
Peel Inlet	4	1.87	(1.47-2.11)	4.5	(1.4-6.3)	4.0	0.5	0.5	1.8
	5	1.55	(1.44-1.85)	3.1	(0.9-4.6)	1.0	0.2	0.2	0.2
	6	1.45	(1.33-1.95)	2.7	((0.6-4.9)	1.0	0.2	0.1	0.4
	7	1.65	(1.60-1.92)	6.0	(3.3-7.6)	20.0	1.4	1.2	8.2
	8	2.47	(1.71-3.59)	8.4	(4.5-14.5)	5.0	2.8	2.0	1.8
Swan-Canning	5	3.92	(2.27-5.57)	14.1	(8.6-20.6)	4.0	9.1	6.2	0.5
Estuary	9	5.00	(4.41-5.50)	19.2	(16.0-21.6)	5.0	9.3	7.0	0.7
	13	4.33	(3.61-5.40)	18.5	(14.6-19.9)	14.0	8.1	5.0	5.0
	16	4.17	(3.41-5.05)	19.5	(15.3-22.6)	7.0	9.7	5.2	1.7
	23A	4.67	(4.25-5.74)	19.2	(16.6-21.8)	15.0	6.4	5.8	4.7

*W/D: Wet to dry ratio by weight; range in parentheses

Table 3. Properties of surface sediments from Collie River.

Site	Depth (m)	W/D ratio	Total phosphorus (□g g^{-1})
Collie 5 North	1.6	3.82	1106
Collie 5 South	2.7	3.24	881
Collie 5 Centre	2.7	1.84	221
Collie 10 West	4.1	3.46	666
Collie 10 East	2.0	4.37	856
Collie 10 Centre	4.1	4.76	1084
Collie 11 North	1.5	2.11	381
Collie 11 South	1.5	1.64	194
Collie 11 Centre	1.5	1.79	267
Collie 13	5.0	6.42	1102

apparently more affected by exchange of water between the inlet and ocean. Sediments from Leschenault Inlet showed similar trends to those of Peel Inlet and Harvey Estuary, where the concentration of iron and aluminium contents were correlated with % organic matter (r^2 = 0.84 and 0.86 for Al and Fe, respectively).

The central sites (sites 5 and 11) of the Collie River had lower W/D ratios than those on the north and south banks, although the ratio at the central site (site 10) remained high (Table 3). The W/D ratios at site 5 (north) and site 10 (east) were relatively high although the water was relatively shallow. Each of these sites was inside a bend in the river, where water flow is reduced and fine particles accumulate, whereas water velocity at the outside of bends discriminates against the settlement of fine particles. Only one sample was collected from site 13, upstream of the confluence with the Brunswick River where the river narrowed considerably.

Phosphorus forms

There were high variations in concentrations of sediment phosphorus between months, sites and estuaries (Table 4). The level of the total phosphorus in Leschenault Inlet was higher than in Peel Inlet (p = 0.013), but lower than in the Swan-Canning Estuary (p = 0.002). Although mean total P appeared low when compared with Harvey Estuary, it was not statistically significant (p = 0.093) at 95% confidence level. The low confidence level of the differences was partly attributable to the small site numbers in Leschenault Inlet, and the large between-site variations in Harvey Estuary.

Sediment total P in the Swan-Canning Estuary was significantly higher than in the Peel Inlet and Harvey Estuary (p = 0.050 and 0.005 respectively).

Organic phosphorus in the Leschenault sediments accounted for 19 to 31% of total P, with an average similar to Harvey Estuary (25%). This proportion was higher than in the Swan-Canning (19.6%). There was no significant difference in organic phosphorus content between Leschenault and Peel Inlet, and between Leschenault Inlet and Harvey Estuary. Organic phosphorus in Leschenault Inlet was significantly lower compared with the Swan-Canning Estuary (p = 0.006). Apatite phosphorus averaged about 37% of the total P in Leschenault sediments, the highest among these estuaries. This may reflect a strong marine influence, as apatite phosphorus can be 5 times higher in ocean sediments than in the Peel-Harvey (Lukatelich & McComb 1986). The concentration of apatite-P was higher in Leschenault than in Peel, but lower than in the Swan-Canning Estuary (p = 0.036 and p = 0.020, respectively). Non-apatite phosphorus averaged about 36% of total P in Leschenault Inlet, comparable with Peel Inlet (36.8%), but lower than in Harvey Estuary (46.1%) and Swan Canning Estuary (56.7%). The concentration of non-apatite P was also lower in Leschenault than in Harvey Estuary and the Swan Canning Estuary (P = 0.032 and 0.021 respectively).

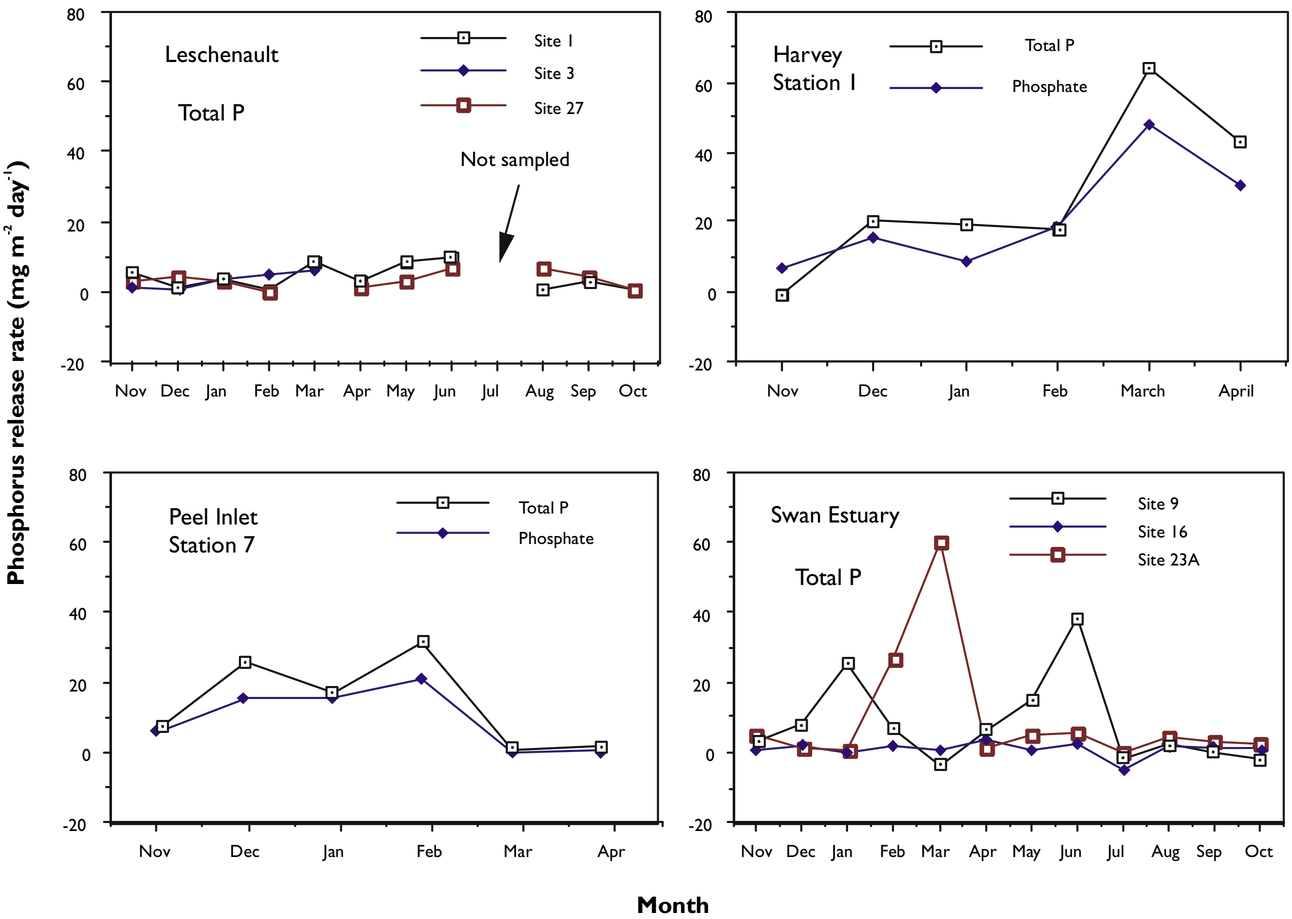

Figure 4. Sediment phosphorus release from intact cores collected from several estuaries south-western Australian. Sampling sites are shown in Fig.1.

Table 4. Forms of sediment phosphorus in Leschenault Inlet, Peel Inlet, Harvey Estuary and the Swan-Canning Estuarine System. Data range in brackets.

Estuaries	Site	Total P (□g g^{-1})	Organic P (□g g^{-1})	%	Apatite P (□g g^{-1})	%	Non-apatite P (□g g^{-1})	%
Leschenault	1	389 (283-379)	74 (39-151)	19.0	144 (55-98)	37.0	158 (57-202)	40.6
	3	313 (211-617)	97 (39-142)	31.0	81 (53-231)	25.9	110 (55-191)	35.1
	27	290 (200-420)	59 (26-97)	20.3	124 (30-218)	42.8	85 (23-216)	29.3
	Mean	**331**	**77**	**23.5**	**116**	**35.2**	**118**	**35.0**
Peel	4	227 (124-321)	62 (124-321)	27.3	56 (8-74)	24.6	95 (8-146)	41.8
	5	159 (107-242)	51(40-91)	32.1	37 (24-61)	23.2	58 (33-108)	36.5
	6	141 (96-217)	49 (27-84)	34.7	34 (15-52)	24.1	45 (28-88)	31.9
	7	217 (217-260)	60 (50-86)	27.6	73 (41-100)	33.6	73 (29-171)	33.6
	8	289 (213-431)	84 (55-181)	29.1	91 (54-150)	31.5	113 (50-201)	39.1
	Mean	**206**	**61**	**30.2**	**58**	**27.6**	**77**	**36.8**
Harvey	1	676 (386-888)	193 (40-91)	28.6	148 (13-198)	21.9	327 (187-390)	48.4
	28	400 (271-583)	100 (80-142)	25.0	107 (64-147)	26.8	177 (132-257)	44.2
	29	469 (441-575)	104 (46-145)	22.2	117 (86-142)	24.9	223 (159-281)	47.5
	30	180 (113-300)	59 (360-130)	32.8	38 (13-73)	21.1	73 (43-107)	40.6
	31	270 (142-797)	64 (30-189)	23.7	62 (32-159)	23.0	122 (56-395)	45.2
	37	477 (221-777)	105 (50-176)	22.0	120 (40-194)	25.2	213 (126-402)	44.7
	P59	545 (179-885)	113 (31-240)	20.7	156 (97-253)	28.6	283 (109-493)	51.9
	Mean	**431**	**105**	**25.0**	**107**	**24.5**	**203**	**46.1**
Swan-Canning	5	1013 (473-2136)	183 (20-648)	18.1	278 (84-1011)	27.4	548 (470-776)	54.1
	9	1689 (1489-3082)	174 (28-1067)	10.3	437 (177-1061)	25.9	1221 (514-1758)	72.3
	13	892 (566-1275)	164 (36457)	18.4	289 (201-441)	32.4	532 (314-944)	59.6
	14A	211 (126-328)	69 (33-101)	32.7	49 (20-83)	23.2	82 (51-123)	38.9
	16	696 (540-1019)	155 (47-236)	22.3	228 (104-330)	32.8	391 (217-737)	56.2
	23A	761 (530-1597)	122 (24-278)	16.0	258 (118-360)	33.9	448 (249-789)	58.9
	Mean	**877**	**145**	**19.6**	**257**	**29.3**	**537**	**56.7**

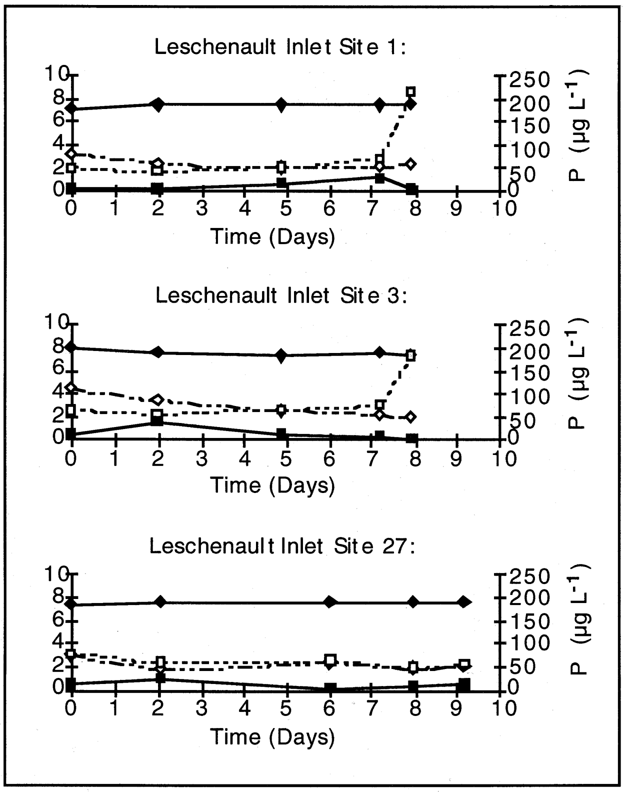

Figure 5. Phosphorus (SRP and TP) release and related pH and DO concentrations (mgL^{-1}) in intact cores collected in March 1990 from Leschenault Inlet. Site 1; Site 3; Site 27. —◆— pH; --◇-- DO; —■— SRP; --□-- TP.

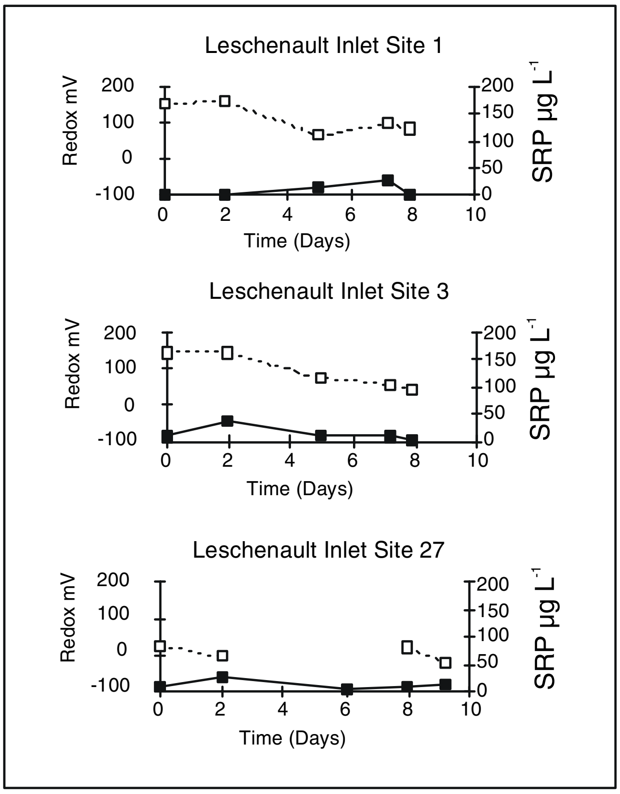

Figure 6. Phosphate (SRP) release and redox potential in intact cores collected in March 1990 from Leschenault Inlet. Site 1; Site 3; Site 27. - - - -□- - - Redox; ——■—— SRP.

Potential for phosphorus release

The laboratory incubations of intact cores suggested that the potential for sediment phosphorus release was relatively small in Leschenault Inlet (Fig 4). In some cases phosphate concentrations in the water column fell during incubation. This occurred in the sediment cores from Site 1 and Site 27 in February to March. Rates of phosphate and total phosphorus release were low in most months compared with other estuaries.

There was little change in water column pH from all three sites in Leschenault Inlet, but DO and redox potential decreased with time (Figs 5, 6). There was no oxygen depletion during incubation, as there was in organic-rich sediments, such as those from Harvey Estuary. Paired cores from Harvey Estuary in the same period showed significant oxygen depletion during incubation. Conditions developed in the water column may favour nutrient release from sediment, but changes in water column concentrations were relatively small. The possibility remains that phosphate in the water column may have been in part transferred to the particulate phase, for example, attached to particle surfaces or taken up by phytoplankton and other microorganisms. The increase in total phosphorus at the end of incubation suggests that such activity could have been involved in altering phosphate concentrations in the water column.

Sediment release rates for phosphate were –15.8 (*i.e.* the water concentrations fell) to 5.6 mg m^{-2} d^{-1} in Leschenault Inlet (Table 5), and the calculated annual average would be –0.11 mg m^{-2} d^{-1}. This is extremely low compared with the estimated annual rate for Harvey Estuary during 1982-1990 (Table 5). Table 6 also shows that phosphate release from the sediments studied is always coupled with ammonium release, though this information is not directly available for Leschenault Inlet.

Interrelations between components

There was a significant correlation between W/D ratio and total phosphorus in Collie River sediments (Fig 7). Similar correlations exist in many other estuaries in south-western Australia (Fig 8), despite difference in trophic status and sediment phosphorus concentrations. The slope of the relationship, however, may differ between systems according to sediment properties and the degree of nutrient enrichment (Hill *et al.* 1991; McComb *et al.* 1998).

W/D ratio was also correlated with the proportion of particles less than 75 µm in Leschenault, Peel-Harvey and Swan-Canning estuaries ($r^2 = 0.74$, $p < 0.01$). There was no correlation between water depth and the other parameters measured in Collie River. This may suggest that water flow, rather than local morphology, is the dominant factor in the distribution of sediment components.

Surface sediments from Leschenault Inlet had a large proportion of fine material, with a particle size finer than in the Peel-Harvey Estuary. Consistent with this, organic enrichment of surface sediment was relatively high. It was higher than in Peel Inlet, comparable with part of Harvey Estuary, but lower than in central Harvey Estuary and the Swan-Canning Estuary.

This paper focused on the redox-related P release,

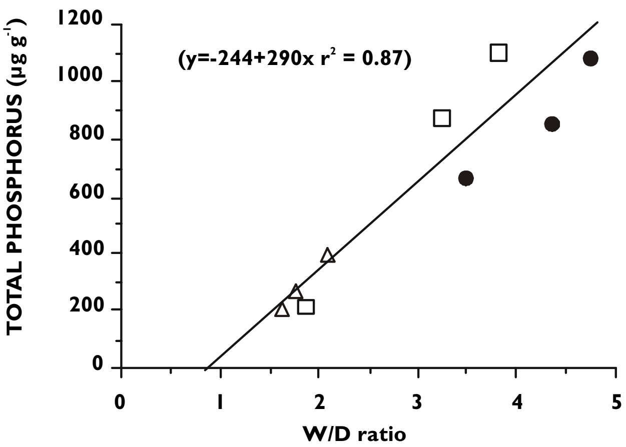

Figure 7. W/D ratio and total phosphorus content in sediments from Collie River. □ Site 5; ● Site 10; △ Site 11.

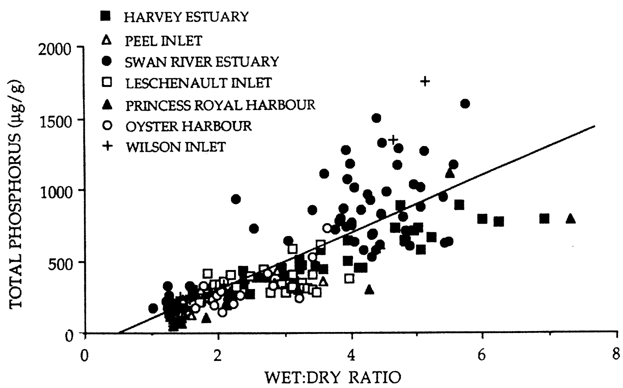

Figure 8. W/D ratio and total phosphorus concentrations in sediments from estuaries of south-west Australia. (y=105.29 + 193.78x; r=0.65).

which was usually driven by bacterial activity and triggered by favorable conditions including high respirable C. Several factors are usually associated with this type of P release, mainly a) the level of organic respiratory C; b) the composition of the sediment P form, and c) their absolute amounts. The organic content in Leschenault Inlet was higher than in Peel Inlet and similar to that of the Harvey Estuary. Sediment oxygen demand associated with the degradability of organic matter was similar to those in the Peel Inlet and Swan-Canning Estuary, though it was lower compared with those in Harvey Estuary (Qiu & McComb unpublished data). Therefore it is difficult to interpret the different P release rates between estuaries by the amount and the nature of organic matter alone. On the other hand, there was no clear indication that the level of 'absolute amount' of any sediment P forms was predominantly higher or lower in Leschenault, which may be responsible for the difference in P release. The proportion of apatite-P to total P, however, appears to be consistent with the P release data. The Leschenault sediments contain a substantial proportion of apatite P, distinctly higher than in Peel, Harvey and Swan-Canning.

At least in part for this reason, the rate of P sediment release remained low in Leschenault Inlet compared with the other estuaries. This low P release may be also related to the overall effects of other factors, such as the relatively low amount of sediment P forms, though this was not strongly supported by the limited sediment data. Likewise, the field conditions should not be neglected, as this type of P release is usually triggered under favorable environmental conditions, such as an increased water, which stimulates microbial development near the sediment-water interface.

Table 5. Phosphate release rate (mg m^{-2} day^{-1}) over 10 days' incubation from Leschenault Inlet sediments, between November 1988 and October 1989.

Station	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
1	1.5	3.6	1.6	-5.2	-0.2	-15.8	5.3	3.6	*	3.4	1.0	0.7
3	5.2	1.2	2.3	1.5	-0.2	-15.4	-	-	*	-	-	-
27	-0.1	2.4	2.1	0.3	-	0.8	1.6	1.6	*	5.6	1.8	0.3

*Samples were not collected because of poor weather conditions.

Table 6. Phosphate and ammonium release rates (± se) of sediments from Station 1 in Harvey Estuary.

	Harvey Estuary		Peel Inlet	
Year	**Phosphate (mg m^{-2} day^{-1})**	**Ammonium (mg m^{-2} day^{-1})**	**Phosphate (mg m^{-2} day^{-1})**	**Ammonium (mg m^{-2} day^{-1})**
1982	24.3 ± 9.6	-	-	-
1983	28.4 ± 4.4	98.3 ± 13.3	-	-
1984	20.6 ± 3.3	194.9 ± 33.8	5.2 ± 2.1	102.4 ± 26.4
1985	19.8 ± 4.0	216.2 ± 51.5	4.5 ± 0.9	128.2 ± 33.0
1986	20.5 ± 4.6	212.5 ± 40.5	4.9 ± 1.7	75.8 ± 16.3
1987	13.1 ± 5.5	202.2 ± 49.0	2.7 ± 1.2	86.2 ± 11.7
1988	5.2 ± 2.4	75.8 ± 14.1	3.0 ± 3.5	63.5 ± 15.2
1989	14.3 ± 4.4	252.8 ± 67.3	8.5 ± 1.7	252.8 ± 67.3
1990	16.7 ± 5.4	-	7.2 ± 2.8	-

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