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Report to the Waterways Commission

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A COMPARATIVE STUDY OF SOME OF THE PHYSICAL AND CHEMICAL CHARACTERISTICS OF THE SEDIMENTS FROM THREE ESTUARINE SYSTEMS IN SOUTH WESTERN AUSTRALIA.

Report to the Waterways Commission

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1. INTRODUCTION

1.1 Background

The relationship between the trophic state of an aquatic system and phosphorus loading has been well documented (Bates and Neafus 1980, Bostrom *et al* 1985, Gilliom 1984, Marsden 1989, Thomas 1973). One of the most unpleasant consequences of eutrophication is the increase in primary production, manifest in Peel Inlet as nuisance blooms of green macro-algae and in Harvey Estuary as the blue green alga *Nodularia spumigena*. The excessive nutrient loading in the two systems and subsequent increased primary production and decreased water quality provide difficult management problems.

Many authors have described the importance of the sediments in phosphorus recycling. The sediments have the ability to both bind and release phosphate, depending on the physical and chemical nature of the sediments (Forsberg 1987) and Bates and Neafus (1980) have described the role that the sediments play as a phosphate buffer, maintaining a constant phosphate concentration in overlying water. Lukatelich (1987) has also pointed out that the factors which determine the significance of the sediments to water quality are the size and composition of the sediment phosphorus store and the potential for phosphorus release. The information that has been obtained in this study can be used in a predictive and interpretative fashion when considering the problem of the potential of sediments for nutrient release in these estuarine systems.

1.1.1 Physical Characteristics

The physical characteristics of the sediments and overlying waters are important factors affecting phosphorus release. For example, Marsden (1989) states that the rate of phosphorus release is dependent on the physical and chemical nature of the sediments and the history of enrichment and flushing rate of the system. Grobler (1981) found phosphorus release to be greatest under mixed conditions, regardless of the oxygen state of the system.

1.1.2 Chemical Characteristics

The chemical composition of the sediment is a major factor determining the potential phosphorus release (Bostrom and Petterson 1982, Forsberg 1987, Marsden 1989). Secondary aluminium and iron compounds, in the form of amorphous hydrated oxides and aluminosilicates, are involved in the sorption of phosphorus in terrestrial soils (Williams *et al* 1971). These compounds have hydroxyl ions in surface positions on the molecule which can readily react with orthophosphate by "exchange adsorption" of the hydroxyl ion for orthophosphate. Conversely, under anoxic conditions, the Fe(III) ions are reduced to Fe(II) and phosphorus is released. Mortimer (1941a,b) described the processes by which phosphate is sorbed to iron(III) under oxic conditions while under anaerobic conditions, iron(III) is reduced to iron(II) and phosphate is released. Ferrous and ferric content in the sediment has been found to be correlated with oxygen content of the sediment (Coey *et al* 1974).

Iron and its redox reactions (Bates and Neafus 1980) and the bacterial activity in the sediment (Bostrom *et al* 1985) play a major role in influencing and controlling phosphate exchange between the sediments and the overlying water body. Bacteria also store phosphorus, under oxic conditions, and bacterial phosphorus release occurs under conditions where the redox potential is reduced so that iron (III) is reduced (Gachter 1987).

The influence of the pH and redox state of the sediment is more pronounced in sediments where iron and aluminium bound phosphorus are dominant (Bostrom *et al* 1985). The presence of iron and aluminium components are also considered important in the mechanism for phosphorus release in the sediments (Forsberg 1987, Gachter 1987, Petterson 1986). Shukla *et al* (1971) and Li *et al* (1972) have stated that the levels of inorganic phosphorus in the sediment and the ability of the sediment to sorb added inorganic phosphorus are controlled by the amorphous gel complex dominated by iron in the sediments.

1.1.3 Sediment Phosphorus Content

The phosphorus fractions present within the sediments are also important in determining potential recycling of phosphorus (Bostrom and Petterson 1982), although there is no significant correlation between the phosphorus content of the sediments and the trophic state of the overlying waters (Lukatelich 1987, Williams *et al* 1972). Not all of the phosphorus present in the sediment is potentially available for release but the algal available phosphorus content of the sediments can be predicted using the inorganic phosphorus content (Grobler 1981). Three forms of sedimentary phosphorus have been defined by Williams et al (1986); apatite phosphorus is that fraction present as orthophosphate bound in the crystal lattices of apatite grains, non-apatite phosphorus is the inorganic orthophosphate fraction not described as apatite, and is considered to be the algal available fraction, and organic phosphorus describes all forms of phosphorus associated with carbon atoms through C-P or C-O-P bonds. The importance of iron and aluminium bound phosphorus in phosphorus release has been discussed and therefore this fraction should be highest in the sediments that exhibit the greatest phosphorus release.

Petterson (1986) has also described the importance of sediment chemistry in influencing phosphorus release. Sediments high in calcium carbonate and/or organic phosphorus were found to release very little phosphorus while sediments with high levels of aluminium or iron bound phosphorus released large amounts of phosphorus. Forsberg (1987) also considers phosphorus release to be highly dependent on the fractional composition of the sediments.

1.2 Study Objectives

This study is part of an ongoing investigation of the relationship between sediment properties and water quality in a number of South-western Australian estuaries, which are collectively concerned with the physical and chemical characterisation of sediments, including their phosphorus content and release of phosphorus to the waters above. The study reported here provides a detailed comparison of the physical characteristics and nutrient status of the surficial sediments in three estuarine systems within and adjacent to the Swan Coastal Plain. In particular, it examines the relationships between phosphorus fractions in the sediment, physical characteristics of the sediment and the trophic state of the water bodies.

The study was carried out from September 1988 until September 1989. Laboratory analyses were used to document the physical characteristics of the sediments, including percentage organic matter, particle size and the wet:dry (W/D) ratio of the sediment, (because of the possible importance of these properties in sediment phosphorus properties). In addition the actual phosphorus content of the sediments was analyzed in terms of the presence of total, organic and inorganic phosphorus because these characteristics of phosphorus content affect the phosphorus release rates. Finally, quantitative numerical comparison, of the three systems, was made so as to determine general relationships which might be more useful in the management of a diversity of systems.

1.3 Study Sites

1.3.1 Swan-Canning Estuary

The Swan-Canning Estuary is located in the Perth metropolitan area (Figure 1.1), and receives river flow from the Avon and Swan Coastal catchments. The Avon catchment totals 119,000 km^2 and feeds the Avon River which rises 370 metres above sea level at Wickepin and becomes the Swan River at Woorooloo Brook. The Swan Coastal catchment (20,000 km^2) drains into the Swan River. The Canning River, which is fed by the Southern River and several freshwater brooks, joins the system on the Coastal Plain.

The Swan-Canning system comprises three broad estuarine basins; Perth and Melville waters, and the Canning Basin; with a relatively narrow and deep channel connecting the basins to the sea. The total estuarine system is approximately 53 km^2 in area. This system is permanently open to the sea, and is relatively deep by compared with the other systems studied attaining a depth of 20m between Melville Waters and Fremantle.

The catchment is largely urban from Fremantle on the coast up to Guildford and is industrialised upstream of Perth city. The upper reaches of the Swan are flanked by market gardens, vineyards and other rural developments and agriculture further inland.

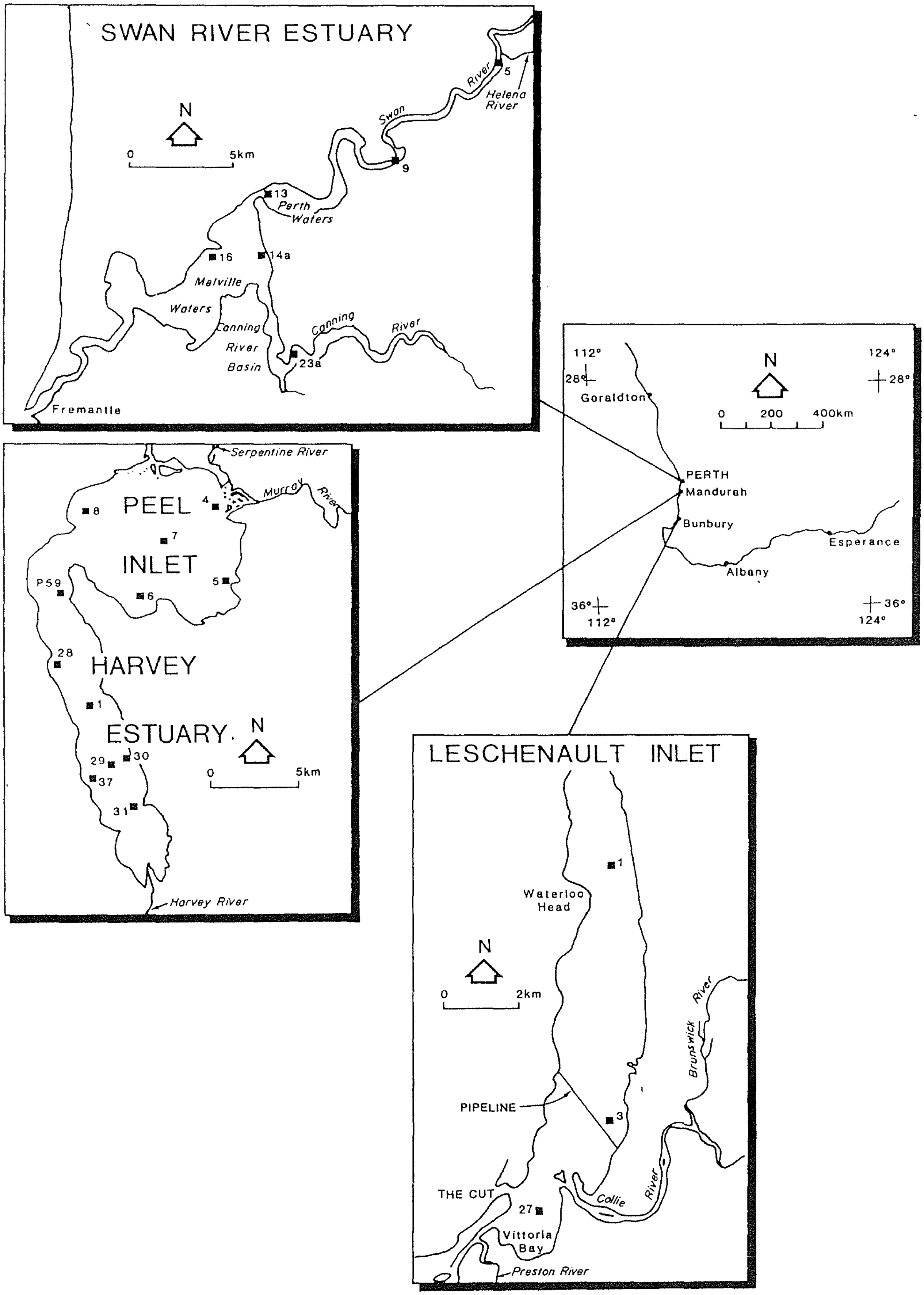


Figure 1: Sampling Sites for the Three Estuarine Systems.

As with the other systems described here, the low tidal range and high rainfall during the winter months results in marked temporal and spatial changes in salinity. The surface waters from Fremantle to the Narrows remain marine during the summer months while the upper reaches of the rivers became brackish. Heavy rainfall during the winter however, may result in the entire estuary becoming fresh. Increased rainfall results in an increase in the external nutrient loading of the system which is an important factor in the nutrient status of the estuary.

The Swan-Canning Estuary has been described as eutrophic (Thurlow *et al.* 1986). Blooms of chlorophytes and euglenophytes have occurred in the upper riverine sections of the estuary while blooms of dinoflagellates, cryptophytes and macrophytes have been observed in the lower reaches of the river (W. Hosja. *pers comm.*). The sediments in the lower reaches of the system are mainly coarse sands with overlying fine silt. Further upstream, the sediments become finer with the organic matter content increasing.

1.3.2 Peel Inlet and Harvey Estuary.

Peel Inlet and Harvey Estuary (Peel-Harvey Estuarine System) are located 75 kilometres south of Perth on the western edge of the Swan Coastal Plain. The system itself is made up of two coastal lagoons connected by a narrow channel 50 metres long and up to 3.5 metres deep (Figure 1.1). Data are presented separately for Peel Inlet and Harvey Estuary.

Peel Inlet is an almost circular basin, approximately 75 km^2 and maximum depth of 2.5m. Harvey Estuary is approximately 60 km^2 in area; a narrow lagoon 20km long and up to 2.5m deep, it is nestled in the depression between two coastal dunes. Both estuaries are of similar volume; Peel Inlet containing $61x10^6$ m^3 and the Harvey Estuary $56x10^6$ m^3.

The system is fed by three rivers. In an average year flow from the Serpentine River, which enters Peel Inlet. contributes some 19% of the total volume of river water entering the system. The Murray and Harvey Rivers which flow into the Peel and Harvey Estuaries respectively contribute, on average, approximately 45% and 36% to the annual river inflow to the Peel-Harvey System. The external nutrient loading from the catchment is related to the river flow, and is highly seasonal.

The Peel and Harvey catchments are dominated by agricultural land use. Clearing of coastal vegetation, use of phosphatic fertilizers, and extensive drainage for agriculture have resulted in excessively high external nutrient loadings to the system. The total catchment for the Peel and Harvey estuaries is approximately 11,300km^2, of which 500km^2 in the Serpentine and Harvey River catchments, and approximately 6,890km^2 in the Murray River catchment remain undammed.

Flushing between marine and estuarine waters is restricted by the narrow channel at the entrance to the Peel Inlet. The mean flushing time in Peel Inlet is approximately 30 days while the flushing time for the Harvey Estuary is approximately 50 days. The daily tidal range in the south west of Australia is approximately 1 m but this is reduced within the estuary by the long, narrow inlet channel and diurnal tidal amplitude in the estuary seldom exceeds 0.1m.

The salinity of the estuarine water varies from almost fresh, during periods of high rainfall and river flow, to hypersaline during the summer months where low river flow and high rates of evaporation may result in salinities in the order of 50 ppt. The systems are dependent on the seasonality of rainfall and river flow and therefore the salinities vary not only between seasons but also between years.

Peel Inlet sediments are predominantly coarse sands along the marginal plateau and fine sands in the central basin. The sediments in Harvey Estuary comprise coarse sands along the eastern margin, silt in the central Harvey basin and fine, muddy silt along the western margin.

Both Peel Inlet and Harvey Estuary are highly eutrophic systems. Nuisance accumulations of aquatic macrophytes, mainly *Chaetomorpha* and *Ulva sp.* occur in Peel Inlet whilst in Harvey Estuary the blue-green alga *Nodularia spumigena* is the major nuisance organism.

1.3.3 Leschenault Inlet.

Leschenault Inlet is located 180 km south of Perth The inlet is a long, narrow and relatively shallow lagoon approximately 27km^2 in area. The maximum depth is approximately 2.0m. The lagoon is connected to the sea by an artificial channel at the southern end.

The catchment is approximately 3,600km^2 in area but of that 2830km^2 are claimed by Wellington Dam, leaving 770km^2. The estuary is fed by the Preston and Collie Rivers. In the years prior to the man-made changes the system was predominantly brackish during the winter. The construction of Wellington Dam and the increased flushing of marine water through the man-made channel has resulted in the estuary becoming predominantly marine. During the summer months a salt wedge travels some 4 kilometres up the Collie River. The catchment area contains forestry and heavy industry, as well as urban and rural land uses.

The sediments in the estuary are similar to those of Harvey Estuary with sands on the eastern margin, silts in the central basin and muddy silt along the western margin.

Leschenault Inlet is considered to be mildly eutrophic. Aquatic macroalgae are dominant in this system, but do not present the same nuisance as in Peel Inlet.

2. MATERIALS AND METHODS

Sediment monitoring was commenced in September 1988. Sediment samples were collected monthly from six sites in the Swan-Canning Estuary and three sites in Leschenault Inlet, and every two months from the five sites in Peel Inlet and seven sites in Harvey Estuary (Figure 1.1).

The sediment was collected from the top 1cm of the sediment at each of the sampling sites by SCUBA diving, returned to the laboratory and stored overnight at 4°C. Next day the sediments were dried at 105°C, ground and stored until analysis. The wet:dry (W/D) ratio was determined by drying a known weight of wet sediment and water content was calculated as (1-(1/(W/D)). Percentage organic matter was determined by loss on ignition (550°C, 1hr).

In July 1989, sediment was collected for analysis by the Chemistry Centre of Western Australia. Analyses were carried out for grain size, % iron, % aluminium, % calcium and % calcium carbonate. In Peel Inlet, Harvey Estuary and Leschenault Inlet the grain size distribution was determined down to 20µm while in the Swan-Canning Estuary the grain size distribution was determined to 2µm.

The methods used for the chemical fractionation of sediment phosphorus were similar to those described by Williams *et al.* (1980), but without the citrate-dithionite-bicabonate (CDB) extraction. Analysis was carried out on 100mg of dried sediment. One molar NaOH was used to extract non-apatite phosphorus, generally considered to be the algal available phosphorus fraction. Apatite phosphorus was extracted using one molar HCl. The released orthophosphate was measured colorimetrically with the acid molybdate/ascorbic acid reagent described by Strickland and Parsons (1972) and measured on a Varian 634 or DMS 90 spectrophotometer.

Total phosphorus was determined by digesting 1g of ashed sediment with concentrated HCl, and organic phosphorus by the difference between the phosphorus content of ashed and non-ashed sediment. Orthophosphate was again determined colorimetrically (Strickland and Parsons 1972).

3. RESULTS

3.1. Sediment Characteristics

3.1.1. Physical Characteristics(W/D Ratio, Water Content, Grain Size Distribution)

The sediment samples for physical analysis were collected in July 1989.

Peel Inlet

STATION	WET:DRY RATIO (W/D)	WATER CONTENT (%)
4	1.87 (1.47-2.11)	43.5 (32.0-52.2)
5	1.55 (1.44-1.85)	34.6 (30.5-46.1)
6	1.45 (1.33-1.95)	31.0 (24.6-48.6)
7	1.65 (1.60-1.92)	38.9 (37.7-47.9)
8	2.47 (1.71-3.59)	55.9 (41.5-72.2)

Table 3.1. Physical Characteristics of Peel Inlet Sediments (Mean and Range, n=6). The W/D ratio and water content data presented here are averages for the monthly data.

The W/D ratios in Peel Inlet ranged from 1.45 at Station 6 to 2.47 at Station 8 (Table 3.1.). The greatest range of values occurred at station 8 (Table 3.1) and this is attributed to the small scale spatial heterogeneity of the sediments. The ranges for sediments from stations 4 and 6 were similar.

Water content of Peel Inlet sediments ranged from 31.0% at station 6 to 55.9% at station 8, with station 8 sediments showing the greatest overall variation; again, the properties were similar at all sites.

In contrast, the grain size analysis showed more interesting differences between sites. The percentage of particles finer than 75 µm ranged from 0.3% at station 6 to 52.3% at station 7 (Table 3.1 and Figure 3.1).

Stations 5 and 6 are situated on the marginal platform while stations 4 and 7 are situated in the central basin and station 8, also in the central basin, previously supported an algal bed. The W/D ratios and water content differed accordingly, i.e. the finer particles settle in the central basin whilst fine organic particles are also associated with the degradation of the algal bed. The coarse sands are associated with the sediments along the marginal platform. Sediment accumulation increases with depth, resulting from the resuspension of sediments by wave action at the shallow sites and sediment settling at deeper, less actively mixed sites (Evan and Rizler 1980, Davis and Ford 1982). This sediment focusing usually results in coarser sediments occurring with low water, organic and nutrient contents and fine, silty

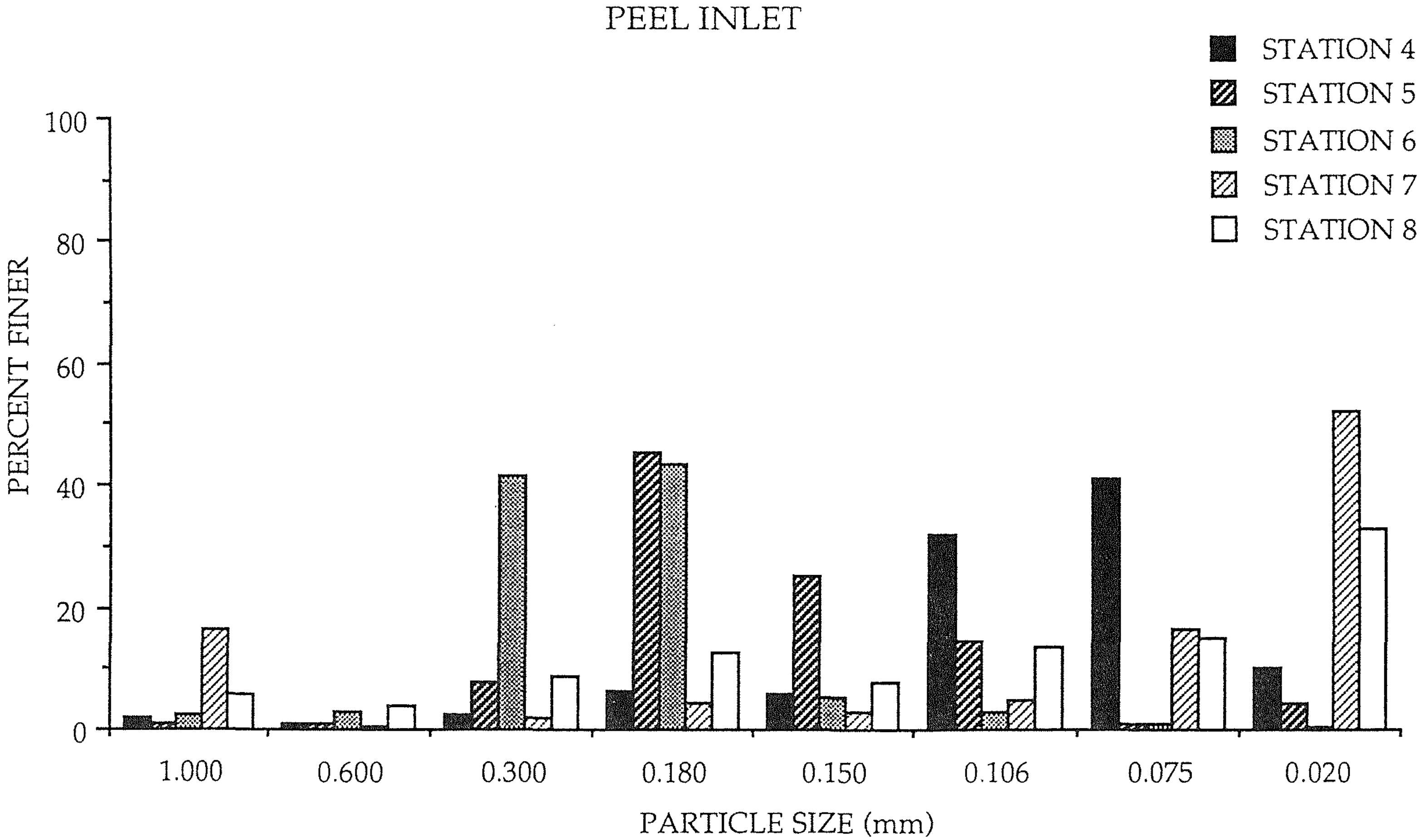


Figure 3.1: Grain Size Data for Peel Inlet

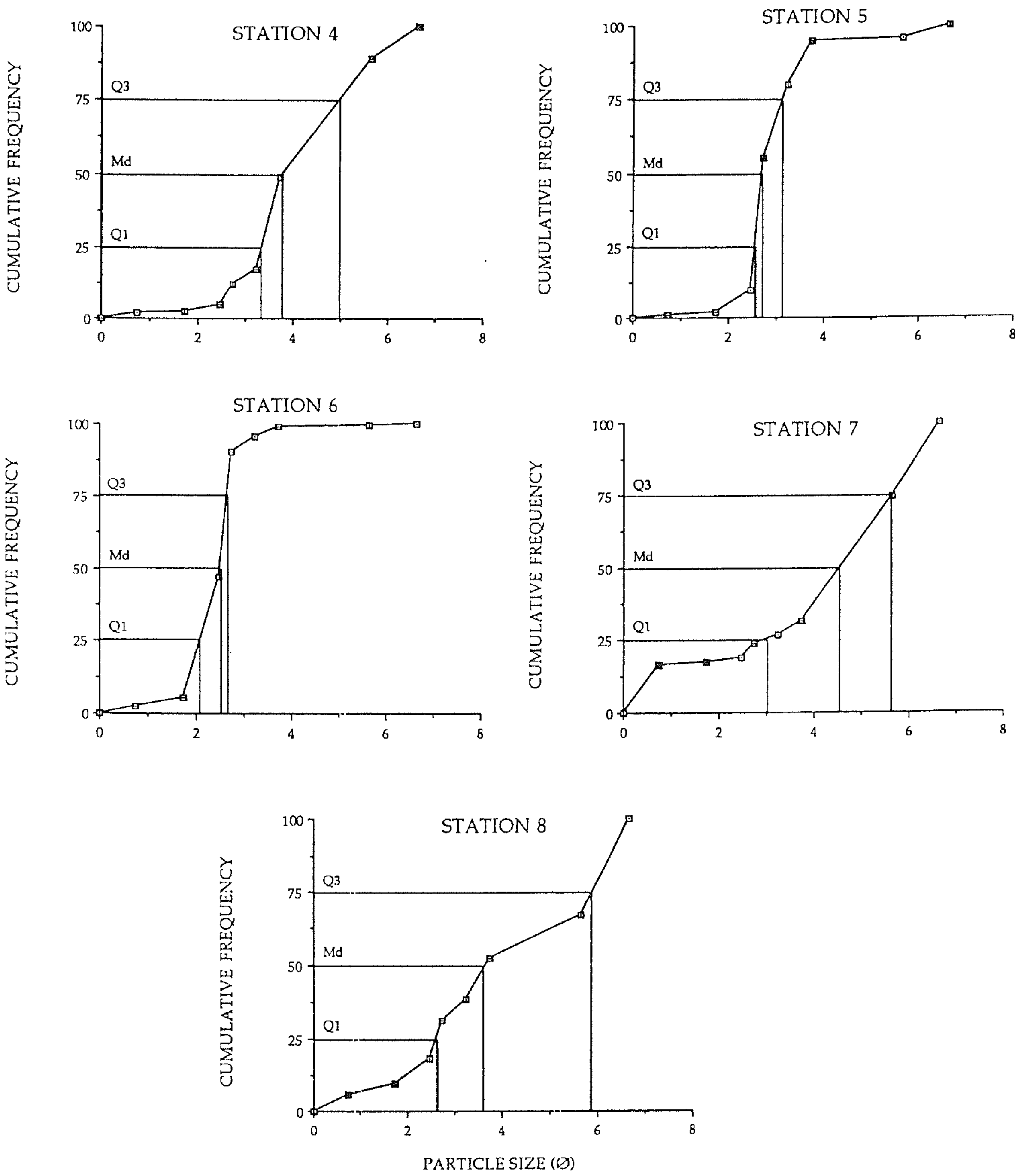


Figure 3.2: Cumulative Grain Size Data for Peel Inlet (where Ø= $\log_2$ of Particle Size (mm)).

sediments occurring with low energy and high water, organic and nutrient contents.

STATION	Q1	Md	Q3	QD	Sk
4	3.4	3.7	4.8	0.7	0.4
5	2.5	2.6	3.1	0.3	0.2
6	2.1	2.4	2.5	0.2	-0.1
7	2.9	4.5	5.6	1.4	-0.25
8	2.6	3.6	2.6	1.6	0.6

Table 3.2. Grain Size Distribution of Peel Inlet Sediments (n=1) where Q1=1st quartile, Md=Median diameter, Q3=3rd quartile, QD=quartile deviation and Sk=skewness.

The sediments in Peel Inlet showed large variation in grain size (Figure 3.1.). Stations 7 and 8 had a small proportion of coarse sands but comprised mainly particles finer than 20µm (Figure 3.1 and Table 3.2). Station 8 sediments were poorly sorted, showing the greatest deviation in mean grain size distribution (QD). The sediments at stations 4 and 5 contained predominantly medium to fine particles and relatively low QD values indicating that these sediments were well sorted. Those from station 7 were poorly sorted, containing the highest median grain size (Md) and the highest proportion of fine particles. Stations 5 and 6 had similar Md and QD values (Figure 3.2). A negative skewness value (Sk) indicated that the grain size cumulative frequency curve (Figure 3.2) was 'skewed' towards a fine particle size distribution while positive Sk value indicated a tendency toward predominantly coarse particles. Sediments from stations 6 and 7 comprised mainly fine particles (Table 3.2) while the remaining sediments comprised coarser grains. The Sk value did not indicate significant skew toward fine or coarse grains.

<u>Harvey Estuary</u>

STATION	WET:DRY RATIO (W/D)		WATER CONTENT (%)	
1	4.88	(2.72-6.92)	78.9	(63.2-85.6)
28	2.69	(2.20-3.53)	61.2	(54.6-71.7)
29	3.55	(2.30-5.05)	70.4	(58.1-75.7)
30	1.30	(1.28-1.58)	30.4	(22.0-38.2)
31	2.21	(1.51-6.00)	43.2	(33.6-83.3)
37	3.41	(1.73-6.25)	62.3	(42.1-83.3)
P59	4.60	(3.14-5.65)	77.5	(68.2-82.3)

Table 3.3. Physical Characteristics of Harvey Estuary Sediments (Mean and Range, n=6). The W/D ratio and water content data presented here are averages for the monthly data.

The sediments from station 30 had the lowest W/D ratio. The W/D ratios for the remaining sediments ranged from 2.21 to 3.55 (Table 3.3). The sediments from stations 1, 31 and 37 showed the greatest variation in bimonthly W/D ratios. The W/D ratios were generally higher in the Harvey than in the Peel (Table 3.3 and Table 3.1), but the ranges suggested that the sediments were generally similar within the Harvey. Station 30 (Table 3.3) had a lower ratio than the other sites. Station 28 had a range of 2.20 to 3.53 while the sediments from station 30 had the narrowest range (1.28-1.58). These differences can be attributed to small scale areal differences between sampling sites. Where there were adjacent sand banks and slopes, the depth of the water can change considerably within a small area, and as a result significant differences may occur in the type of sediment in the samples.

The water content of the sediments ranged from 30.4% to 78.9% . The greatest variation in bimonthly data occurred at stations 1, 31 and 37 (Table 3.3).

STATION	Q1	Md	Q3	QD	Sk
1	2.5	5.8	6.1	1.8	-1.5
28	2.8	3.6	2.9	1.55	0.75
29	0.6	4.0	6.1	2.75	-0.65
30	2.3	2.5	2.7	0.2	0
31	2.4	2.6	3.1	0.35	0.15
37	2.1	2.4	2.6	0.25	-0.05

Table 3.4. Grain Size Distribution of Harvey Estuary Sediments (n=1) where Q1=1st quartile, Md=Median diameter, Q3=3rd quartile QD=quartile deviation and Sk=skewness.

The percentage of particles finer than 75µm was lowest at stations 30 and 31 with 8.3% and 8.8% respectively. Station 37 sediments comprised 17.0% particles finer than 75µm. The sediments from stations 1, 28 and 29 had similar percentages of fine particles with 58.9% at station 1, 33.3% at station 28 and 47.8% at station 29. Data from station P59 is not presented here because the sample was not analysed. (The percentage of particles finer than 75µm was estimated to be 85% by the Western Australian Chemistry Centre.)

Stations 28 and 37 occur along the western margin of the estuary which consisted of predominantly muddy silts. The fine proportion of particles in the sediment was highest for the central basin, stations P59, 1 and 29. Station 30 is located on the eastern margin where the sediments comprised predominantly coarse sands. The grain size distribution in the sediments of Harvey Estuary also showed a large variability (Figures 3.3 and 3.4). The median grain diameter ranged from 2.4 at station 37 to 5.8 at station 1. The skewness of the particle size distribution from stations 1 and 29 tended towards coarse particles whilst the sediments from station 28 tended towards finer grains. The sediments from station 1 had an Sk value of -1.5

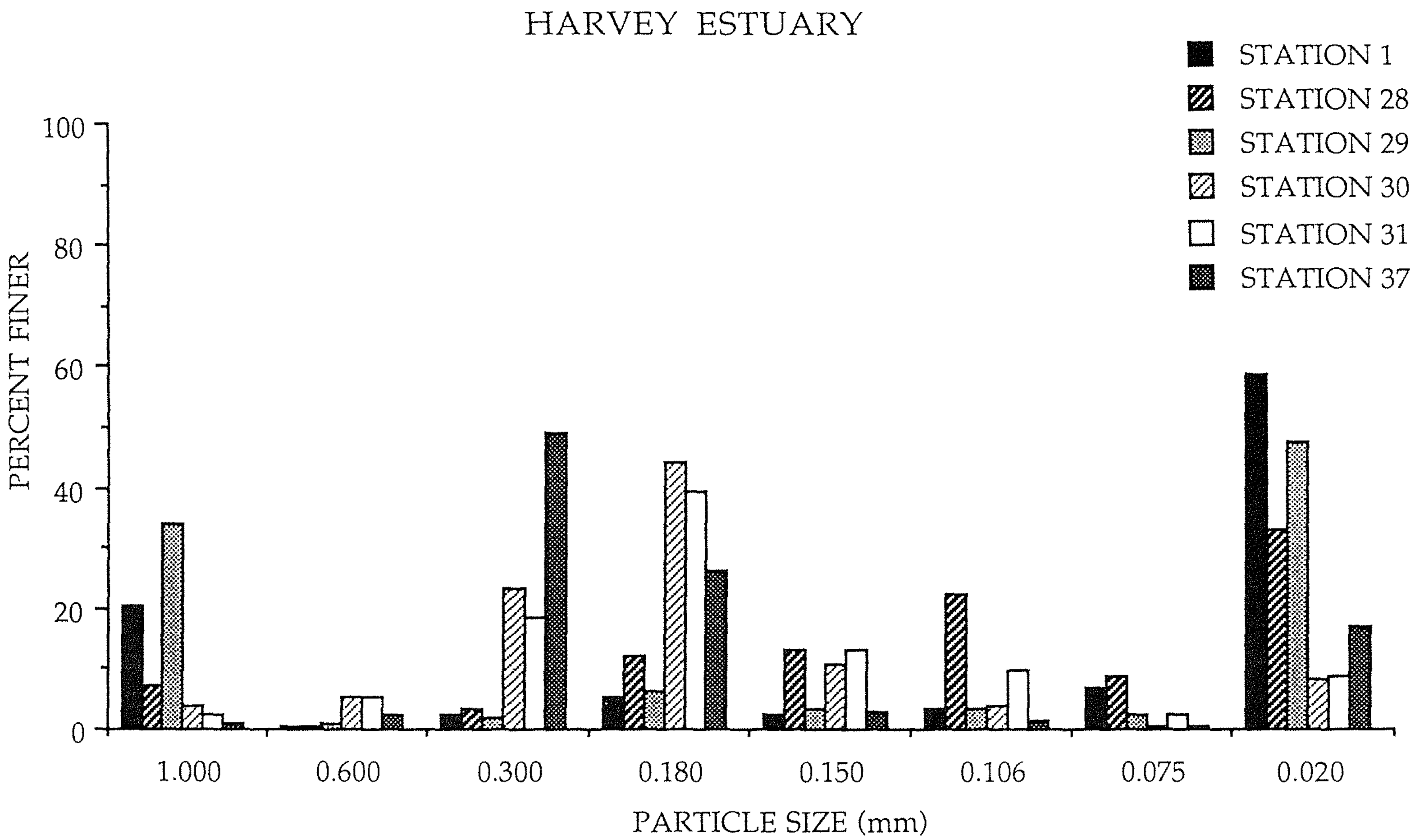


Figure 3.3: Grain Size Data for Harvey Estuary.

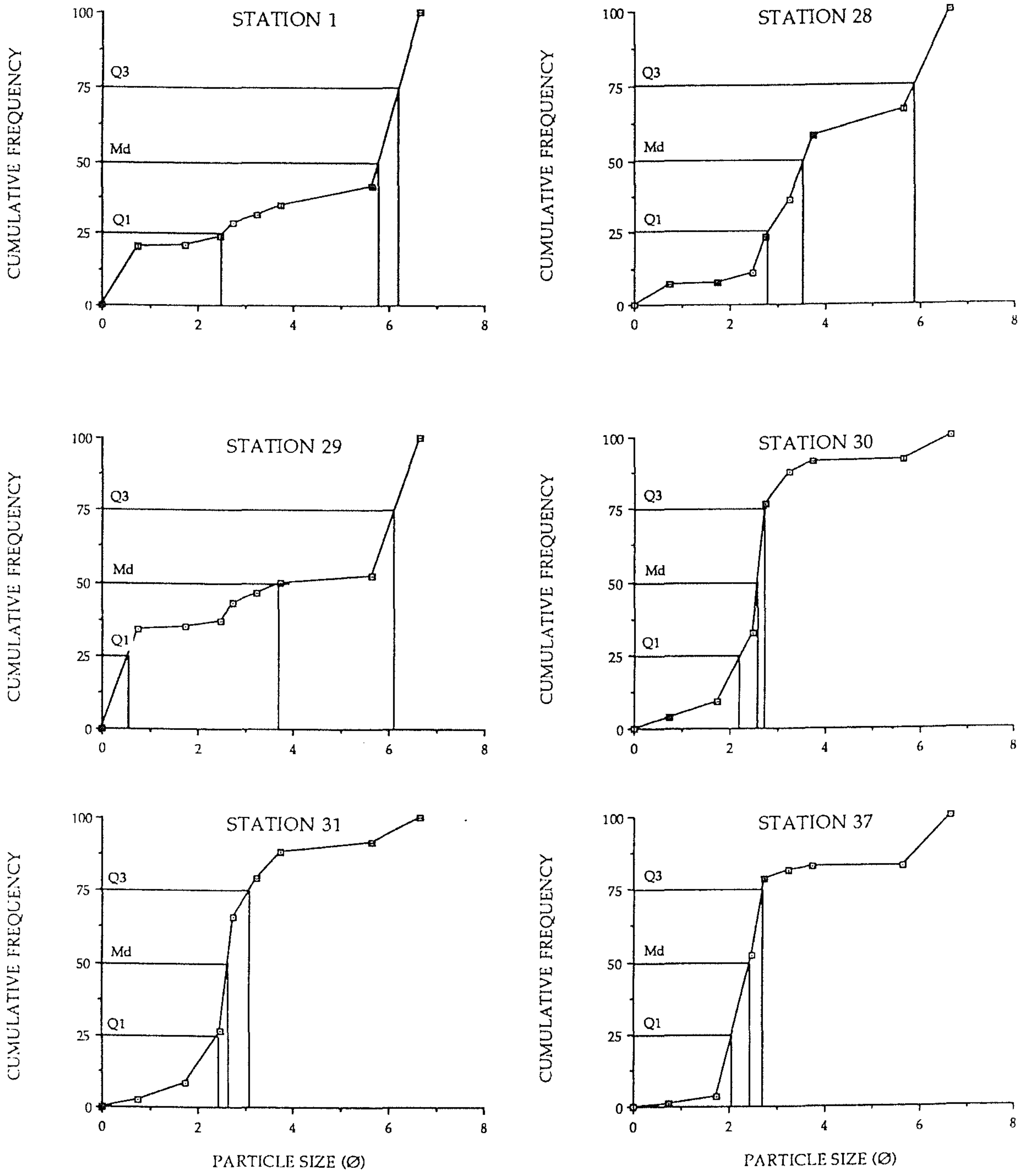


Figure 3.4: Cumulative Grain Size Data for Harvey Estuary (where Ø= $\log_2$ of Particle Size (mm))

which indicated a significant composition of fine particles. The remaining sediments had negligible Sk values.

Swan-Canning Estuary

The W/D ratio of the sediments from the Swan-Canning Estuary ranged from 1.50 at Station 14A to 5.00 at Station 9. The greatest variation in W/D ratios occurred at station 5, 2.27-5.57, whilst sediments from stations 13, 16 and 23A had relatively similar ranges. Sediments from stations 9 and 14A had the narrowest range of W/D ratios. In comparison to ranges in sediment W/D values from Peel Inlet and Harvey Estuary this range is relatively low, suggesting that the sediments in the Swan Canning Estuary are more spatially homogeneous than those of either Peel Inlet or Harvey Estuary, at the sites sampled.

STATION	WET:DRY RATIO (W/D)		WATER CONTENT (%)	
5	3.92	(2.27-5.57)	63.1	(55.9-82.1)
9	5.00	(4.41-5.50)	79.2	(77.3-80.7)
13	4.33	(3.61-5.40)	76.8	(72.3-81.5)
14A	1.50	(1.03-1.58)	21.3	(3.2-36.7)
16	4.17	(3.41-5.05)	76.0	(70.7-80.2)
23A	4.67	(4.25-5.74)	78.8	(76.1-82.6)

Table 3.5. Physical Characteristics of the Swan-Canning Estuary Sediments (Mean and Range, n=12). The W/D ratio and water content data presented here are averages for the monthly data.

The water content of the Swan-Canning sediments ranged from 21.3% at station 14A to 79.2% at station 9 while the greatest variation occurred at station 5.

STATION	Q1	Md	Q3	QD	Sk
5	6.0	6.7	7.2	0.6	-0.1
9	6.6	6.9	7.3	0.35	0.05
13	6.0	6.8	7.2	0.6	-0.2
14A	1.7	2.1	2.5	0.4	0
16	6.2	6.8	7.1	0.45	-0.15
23A	5.8	6.2	6.8	0.5	0.1

Table 3.6. Grain Size Distribution of the Swan-Canning Estuary Sediments (n=1) where Q1=1st quartile, Md=Median diameter, Q3=3rd quartile, QD=quartile deviation and Sk=skewness.

Grain size analysis of these sediments indicated that the sediment fraction finer than 75µm ranged from 4.0% at station 14A to 97.0 % at station 9 (Table 3.5). These results also indicated that the Swan-Canning sediments were of a similar grain size conformation, with the exception of Station 14A (Table

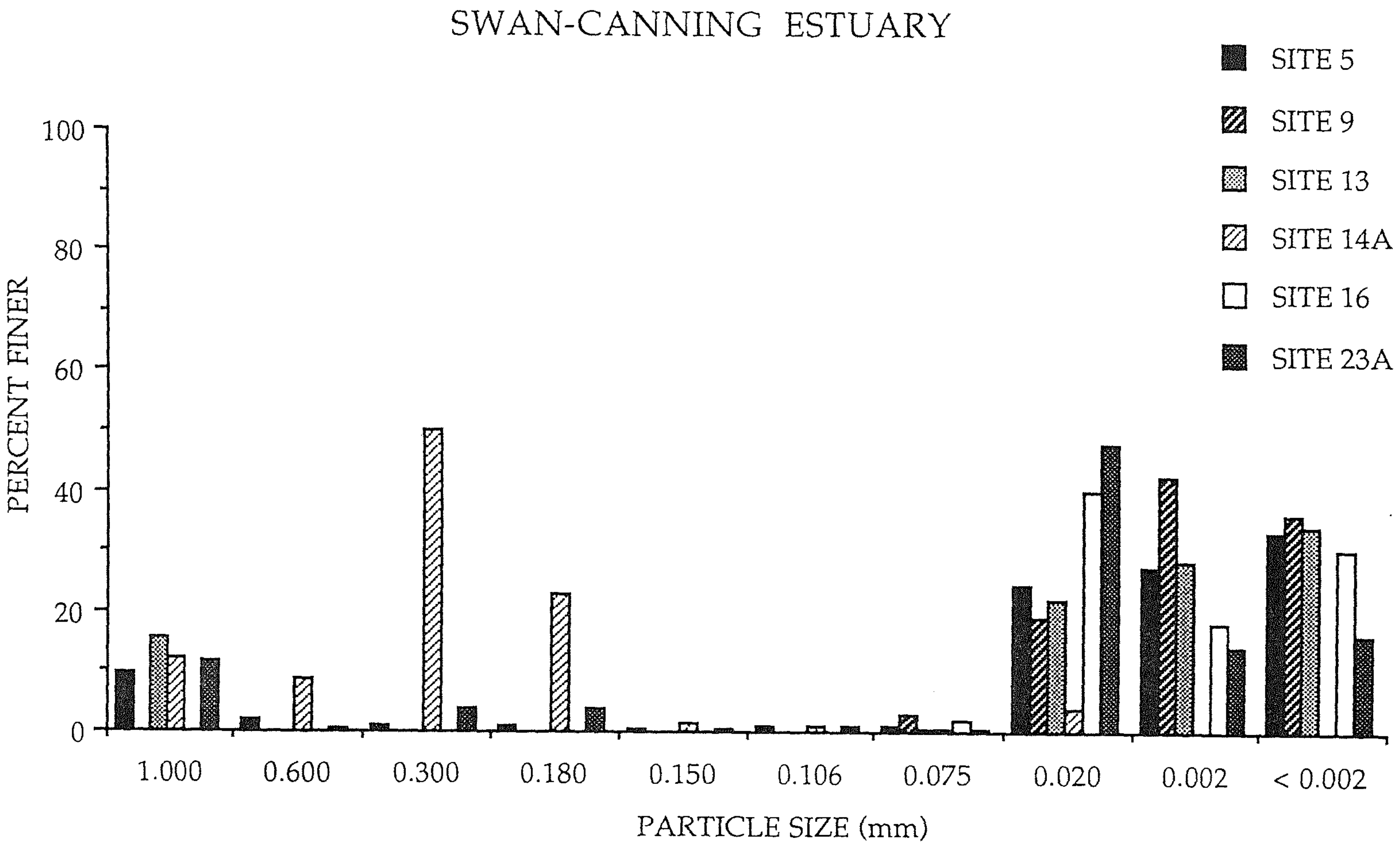


Figure 3.5: Grain size Data for the Swan-Canning Estuary.

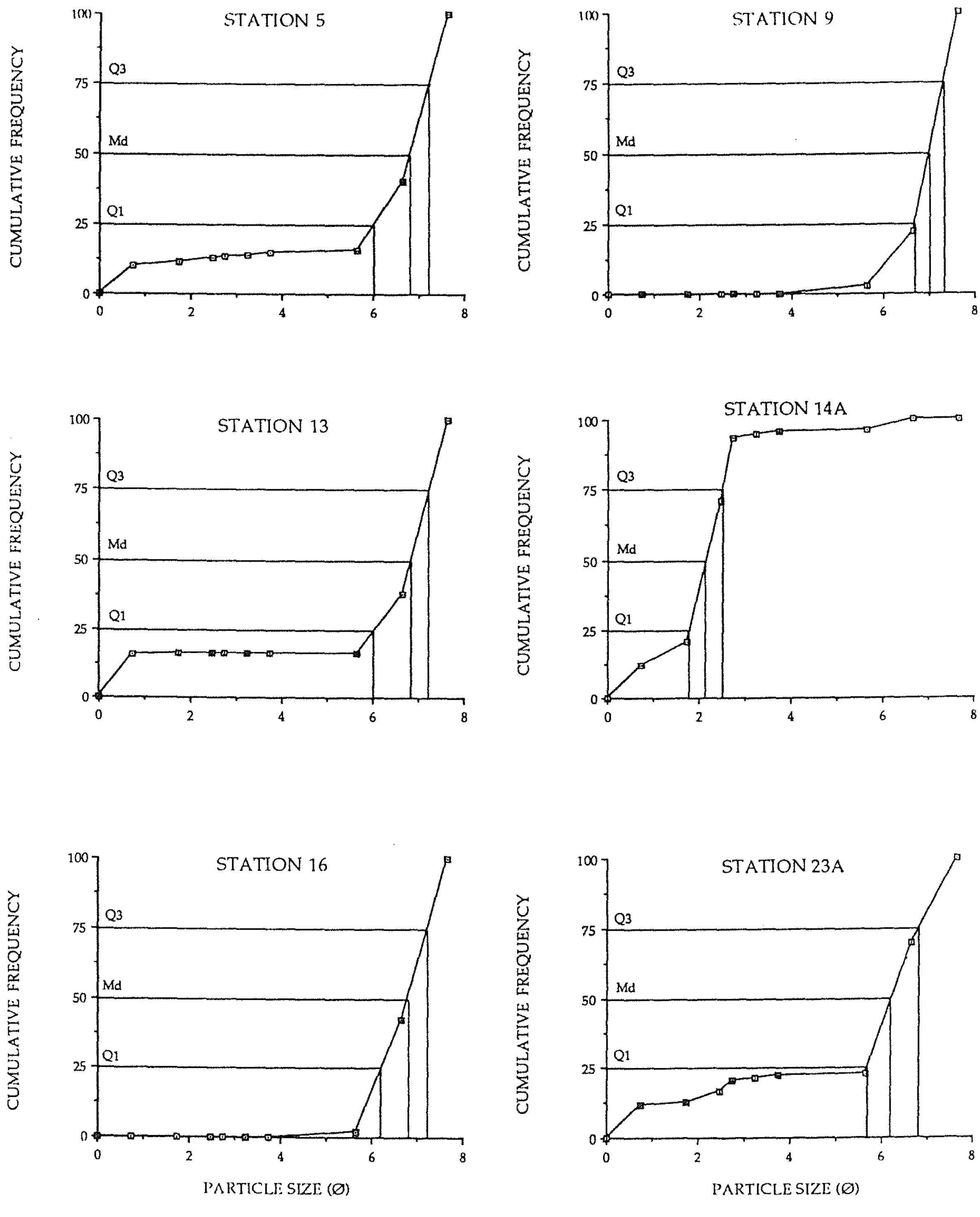


Figure 3.6: Cumulative Grain Size Data for the Swan-Canning Estuary (where Ø= $\log_2$ of Particle Size (mm)).

3.5.). The sediments mainly consisted of particles 20μm or less (Figure 3.5) but station 14A, the shallowest site in the estuary, comprised predominantly coarse sands. The variation in W/D ratio, water content and grain size distribution between sites in the Swan-Canning sediments was largely attributable to depth which ranged from approximately 0.5m at station 14A to 5.0m at station 16 in Melville Waters.

The QD values for the sediments in the Swan-Canning Estuary were relatively low, ranging from 0.4 at station 14A to 0.6 at stations 5 and 13, indicating that the sediments throughout the system were well sorted (Figure 3.6., Table 3.6.). The Md values were similar at all stations, except for Station 14A where a comparatively higher Md value indicated a larger median grain size. Once again, this pattern reflected the effects of depth on the distribution of sediments. Sediment focusing has resulted in the accumulation of fine, silty particles in the deeper and undisturbed sites. The Sk values were also relatively low and therefore did not indicate any particular trend toward large or small particles.

Leschenault Inlet

STATION	WET:DRY RATIO (W/D)		WATER CONTENT (%H2O)	
1	2.83	(2.79-3.97)	62.7	(64.2-74.8)
3	3.08	(1.85-4.50)	68.8	(45.8-77.8)
27	2.11	(1.72-3.41)	50.7	(37.0-70.7)

Table 3.7. Physical Characteristics of Leschenault Inlet Sediments (Mean and Range, n=12). The W/D ratio and water content data presented here are averages for the monthly data.

The W/D ratios of the sediments from stations 1 and 3 in the Leschenault Inlet were relatively similar, ranging from 2.11 at station 27 to 3.08 at station 3 (Table 3.7). The range of W/D ratios was greatest at station 3 (1.85-4.50), situated in the center of the inlet adjacent to the SCM pipeline. There was a greater depth gradient at this station than at the other stations which showed less small scale spatial heterogeneity. The water depth of the stations sampled in Leschenault Inlet ranged from 0.5m at station 1 to approximately 2.0m at station 3. The sediment water content ranged from 50.7% at station 27 to 68.8% at station 3. The greatest variation in water content occurred, once again, at station 3.

Grain size analysis indicated that the percentage of particles finer than 75μm ranged from 87.0% at station 1 to 40.4% at station 27, with 61.8% occurring at station 3. Figure 3.12 shows that the grain size of these sediments was predominantly less than 20μm, particularly at station 1. The sediments from stations 3 and 27 contained a higher percentage of coarse particles and a greater range of grain sizes, reflected in the variation about the median grain size, described by the quartile deviation (QD).

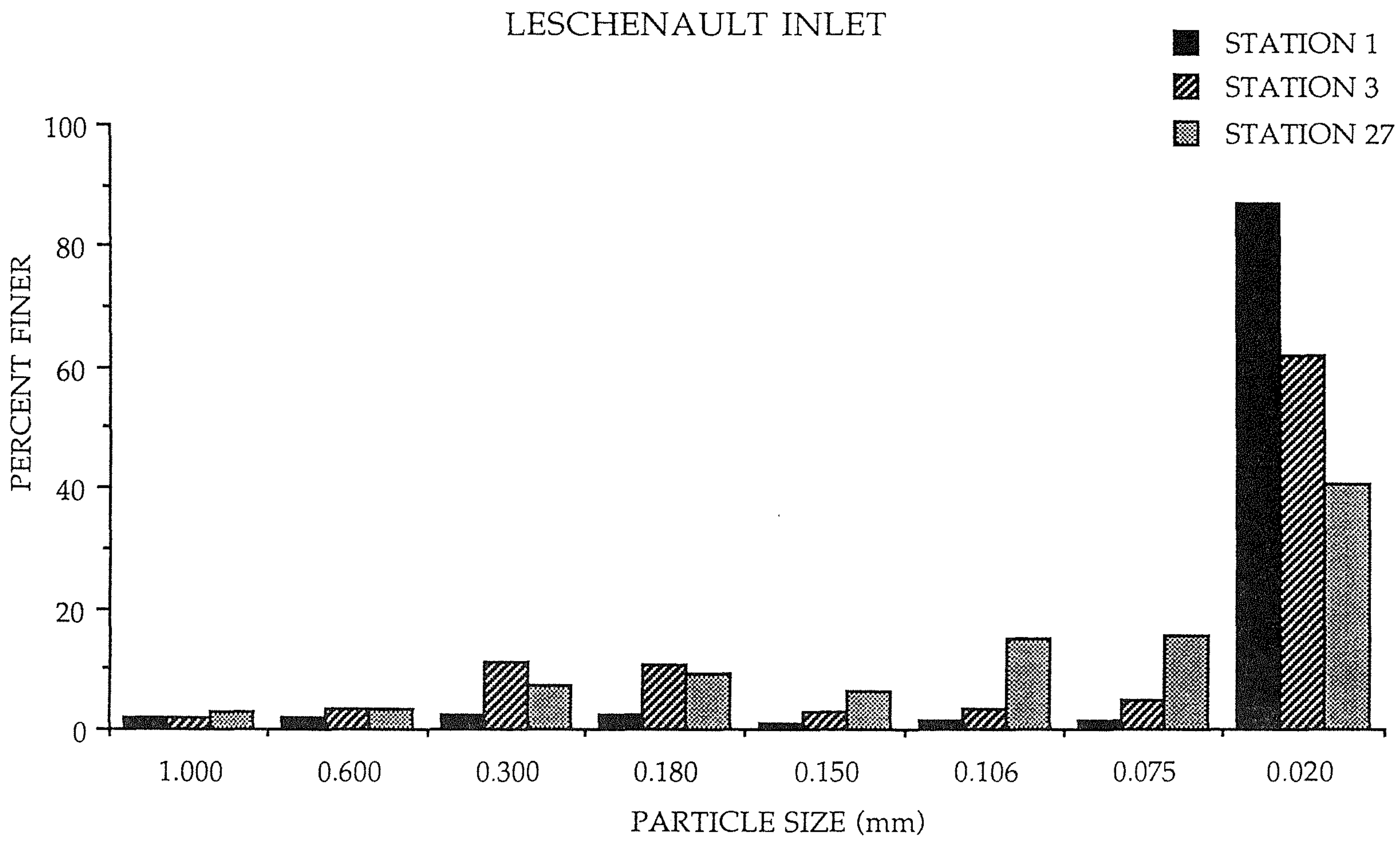


Figure 3.7: Grain size Data for Leschenault Inlet.

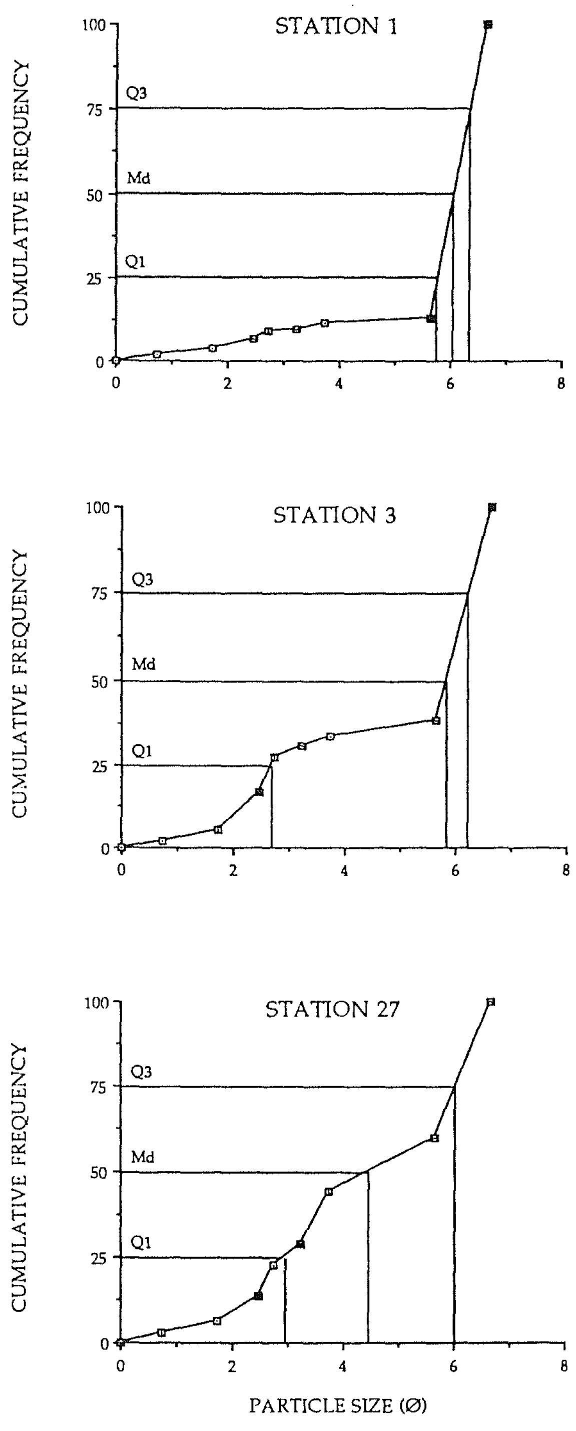


Figure 3.8: Cumulative Grain Size Data for Leschenault Inlet (where Ø= $\log_2$ of Particle Size (mm)).

STATION	Q1	Md	Q3	QD	Sk
1	5.8	6.0	6.2	0.2	0
3	2.6	5.9	6.2	1.8	0.01
27	2.9	4.4	6.0	1.55	-0.29

Table 3.8. Grain Size Distribution of Leschenault Inlet Sediments (n=1) where Q1=1st quartile, Md=Median diameter, Q3=3rd quartile, QD=quartile deviation and Sk=skewness.

The sediments from stations 3 and 27 had higher QD values than those of station 1, indicating that the sediments from these stations were poorly sorted (Figure 3.8 and Table 3.8). The median grain size of the sediments from stations 1 and 3 was similar while the Md value from station 27 sediments indicated a lower median grain size. The Sk values for the sediments from stations 1 and 3 were negligible but an Sk value of -0.29 for station 27 sediments indicated that the cumulative frequency of particle sizes was skewed towards coarse particles.

Comparisons Between Estuaries

These data do not indicate any marked differences between the four systems. The results from Harvey Estuary and the Swan-Canning Estuary have shown a greater range of values than those of the other two systems but this may be attributed to the choice of sampling sites in this survey rather than a reflection of any real differences between the systems.

Sediment type, as expressed by W/D ratio, water content and grain size, was clearly related to the geomorphological features of the respective estuaries. Sediment focusing has resulted in the occurrence of the finest particles at the deepest sites, particularly in the Swan-Canning Estuary and the central Harvey basin but these particles are also associated with the fine silts occurring along the western margin of Harvey Estuary and the remnant algal bed on the western margin of Peel Inlet.

3.1.2. Chemical Characteristics. (%Organic Matter, %CaCO3, %Fe, %Al, %Ca)

Peel Inlet

The percentage of organic matter in the sediments from Peel Inlet ranged from a mean of 2.7% at station 6 to 8.4% at station 8 (Table 3.9). The organic matter content of the sediments occurring along the marginal platform (stations 5 and 6) were relatively low, and there were higher concentrations of organic matter in the central basin (stations 4 and 7). Station 8, situated on a remnant algal bed, contained the highest proportion of organic matter; this site also showed the greatest variation in organic matter content.

The percentage of calcium carbonate in the sediments was clearly highest at station 7 which also contained the highest percentage of calcium. The ratio of calcium to calcium carbonate ranged from 20% in the sediments from station 5 to 45% in the sediments from station 4. There was no clear relationship between the ratio of calcium to calcium carbonate and sediment type or distance from the entrance channel.

STATION	%ORGANIC MATTER (n=6)	% CaCO3 (n=1)	% Al (n=1)	% Fe (n=1)	% Ca (n=1)
4	4.5 (1.4-6.3)	4.0	0.5	0.5	1.8
5	3.1 (0.9-4.6)	1.0	0.2	0.2	0.2
6	2.7 (0.6-4.9)	1.0	0.2	0.1	0.4
7	6.0 (3.3-7.6)	20.0	1.4	1.2	8.2
8	8.4 (4.5-14.5)	5.0	2.8	2.0	1.8

Table 3.9. Chemical Characteristics of the sediments from the Peel Inlet (Mean and Range from bimonthly data).

The aluminium and iron content was highest in the sediments at station 8, followed by station 7 while the remaining sediments contained less than 1%. The presence of aluminium and iron was positively correlated to organic matter.

Harvey Estuary.

The organic matter content of Harvey estuary sediments ranged from 2.3% to 18.63% (Table 3.10). The highest organic matter content occurred at station 59. These results are related to sediment type and depth. Stations 1 and P59 are situated in the central basin where the depth is greatest and the finest particles accumulate. Station 30 is located on the eastern margin of the estuary and the sediments consist predominantly of coarse sands with very little organic matter. The remaining stations occur along the western margin where the sediments consist predominantly of muddy silts and some organic matter accumulates in the lee of the prevailing winds. Sediment focusing has resulted in the accumulation of these fine sediments in sheltered areas where less mixing occurs.

STATION	%ORGANIC MATTER (n=6)	% CaCO3 (n=1)	% Al (n=1)	% Fe (n=1)	% Ca (n=1)
1	17.72(12.3-22.0)	9.0	6.0	3.8	2.9
28	8.73 (1.0-11.9)	6.0	2.6	1.8	2.1
29	10.84(8.0-17.6)	35.0	4.2	2.6	14.4
30	2.30 (1.0-3.5)	2.0	0.8	0.5	0.6
31	5.38 (1.8-19.0)	3.0	1.0	0.6	1.0
37	9.49 (3.0-18.4)	1.0	1.8	1.2	0.2
P59	18.63(11.7-22.0)	9.0	7.6	5.5	1.6

Table 3.10. Chemical Characteristics of the sediments from the Harvey Estuary (Mean and Range of bimonthly data).

The percentage content of calcium carbonate was clearly highest in the sediments from station 29, which contained 35%; the highest levels of calcium were also found in station 29 sediments; the remaining sediments contained less than 3.0%. The ratio of calcium to calcium carbonate ranged from 18% at station P59 to 41% at station 29. Stations 1, 28, 30 and 31 had similar ratios. These ratios were not clearly related to sediment type or distance from the mouth of the estuary although the lowest calcium to calcium carbonate ratio occurred at station P59 which had the highest proportion of organic matter.

The iron and aluminium content was highest in sediments from the central basin; station P59 contained 7.6% aluminium and 5.5% iron. Iron and aluminium were again associated with the presence of organic matter , as they were in Peel Inlet.

Swan-Canning Estuary.

Similar percentages of organic material were found in the sediments from four of the six sampling stations in the Swan-Canning Estuary (Table 3.11), with much lower levels at station 14A. The greatest variation in organic matter content was measured at station 5 but the ranges were similar at the other sites.

STATION	% ORGANIC MATTER (n=12)	%CaCO3 (n=1)	%Al (n=1)	%Fe (n=1)	%Ca (n=1)
5	14.1 (8.6-20.6)	4.0	9.1	6.2	0.5
9	19.2 (16.0-21.6)	5.0	9.3	7.0	0.7
13	18.5 (14.6-19.9)	14.0	8.1	5.0	5.0
14A	1.8 (0.3-4.4)	2.0	0.4	0.4	0.7
16	19.5 (15.3-22.6)	7.0	9.7	5.2	1.7
23A	19.2 (16.6-21.8)	15.0	6.4	5.8	4.7

Table 3.11. Chemical Characteristics of the sediments from the Swan-Canning Estuary (Mean and Range of monthly data).

The percentage of calcium carbonate ranged from 2% at station 14A to 15% at station 23A. The calcium content of the sediments was highest at station 9, and lowest at stations 5 and 14A. The ratio of calcium to calcium carbonate ranged from 12.% at station 5 to 35.7% at station 13. A trend was detected between the ratio of calcium to calcium carbonate and the distance from the estuary mouth. There are also indications of a relationship between this ratio and depth. The lowest ratios occurred at the deepest sites in the riverine reaches of the estuary whilst the highest ratios of calcium to calcium carbonate occurred at the marine sites.

The aluminium content ranged from 0.4% to 9.7% and with the exception of those from station 14A, the Swan River sediments contained a relatively high proportion of aluminium. Iron content ranged from 0.4% to 7.0%. Overall, the sediments also contained a relatively high proportion of iron. There is a relationship between aluminum and iron content and sediment type. The sediments collected in the survey are predominantly fine silts and clays, with the exception of those from station 14A which comprise coarse sands, in which there are presumably high concentrations of iron and aluminium complexes.

Leschenault Inlet

The organic content of the sediments in Leschenault Inlet ranged from 8.6% to 12.1%. Station 1 sediment organic matter was similar to that of station 27 (Table 3.12.) and the range was greatest at station 27 (3.9% to 15.6%).

STATION	% ORGANIC MATTER (n=12)	% CaCO3 (n=1)	% Al (n=1)	% Fe (n=1)	% Ca (n=1)
1	11.17(9.8-15.2)	13.0	3.6	4.4	13.0
3	12.08(5.7-14.9)	8.0	3.4	4.0	2.5
27	8.60 (3.9-15.6)	24.0	1.5	1.9	2.4

Table 3.12. Chemical Characteristics of the sediments from the Leschenault Inlet (Mean and Range of monthly data).

The highest percentage of calcium carbonate occurred at station 27, while the calcium content was highest in the sediments from station 1. The ratio of calcium to calcium carbonate was highest at station 1 where 100% of the calcium was accounted for by calcium carbonate. This value is likely to be overestimated. The ratio at station 27 was 10.0% and at station 3, 31.3%.

The levels of aluminium and iron were highest at station 1 and lowest at station 27. The sediments from Leschenault Inlet showed similar trends to those of both Peel Inlet and Harvey Estuary where there was a relationship between the occurrence of iron and aluminium and the presence of organic matter.

Comparison Between Estuaries

Overall, the sediments from each of the four systems showed similar chemical characteristics. Peel Inlet sediment had the lowest organic matter content. The highest sediment organic matter content was found in the Swan-Canning Estuary at the deepest sites, which contained the finest sediments. The Harvey and Swan-Canning estuaries contained the greatest variation in organic matter content, for the sites sampled.

Each estuary had one or more site with high levels of calcium carbonate and there was generally a high percentage of calcium at these sites. There was not a clear difference between the four systems in either the calcium carbonate or calcium content, but the calcium/calcium carbonate concentrations in the sediments from the Leschenault Inlet, particularly at stations 1 and 28, were marginally higher than at the sites in the other three systems. There was evidence of a relationship between depth, distance from the estuary mouth and the ratio between calcium and calcium carbonate in the sediments from the Swan-Canning Estuary but this relationship could not be seen in data from the other three systems where sediments were only taken from the basins.

There is evidence that the proportion of iron and aluminium in the sediments of the four estuaries is related to the organic matter of their sediments. The sediments from the sampling stations in the Swan-Canning Estuary contained a higher percentage of iron and aluminium (with the exception of station 14A) even where the sediments have comparative W/D ratios. The soils in the Swan catchment are naturally rich in iron and aluminium complexes (R.J. Lukatelich *pers. comm.*) which is reflected in these higher values. Sediment focusing has concentrated these particles in the deeper, lower energy sites where a high W/D ratio and organic matter content also occurred.

3.2. Sediment Phosphorus Fractions.

Peel Inlet

Table 3.13 includes the phosphorus concentration, range and proportion of the three phosphorus fractions to total phosphorus at each sampling site. The phosphorus content of the sediment at station 8 was the highest in Peel Inlet where organic P made up 29% of the phosphorus present, apatite phosphorus 32% and non apatite phosphorus 39%. The lowest concentration of sediment total phosphorus occurred at station 6, where where there was a relatively high proportion of organic phosphorus.

STATION	TOTAL P (µg/g)	ORGANIC P (µg/g)	(%)	APATITE P (µg/g)	(%)	NON-APATITE P (µg/g)	(%)
4	227 (124-321)	62 (124-321)	29	56 (8-74)	26	95 (8-146)	45
5	159 (107-242)	51 (40-91)	35	37 (24-61)	25	58 (33-108)	40
6	141 (96-217)	49 (27-84)	38	34 (15-52)	27	45 (28-88)	35
7	217 (217-260)	60 (50-86)	30	73 (41-100)	35	73 (29-171)	35
8	289 (213-431)	84 (55-181)	29	91 (54-150)	32	113 (50-201)	39

Table 3.13. Sediment Phosphorus Fractions from the Peel Inlet (Mean, Range and Proportion of Total P (%), n=6).

In theory, the sum of the phosphorus fractions equals the amount of total phosphorus present in the sediment. The difference between the analytical and calculated fractions of total phosphorus is a residual phosphorus value which is, between 5% and 10% in our data.

The proportion of organic phosphorus was approximately 30% at all sites; stations 5 and 6 had rather higher values but the ranges were large. Apatite phosphorus comprised approximately 25% of the total phosphorus fraction in sediments from stations 4, 5 and 6 but stations 7 and 8 comprised 35% and 32% apatite phosphorus, respectively. The proportion of non apatite phosphorus ranged from 35% to 45%.

The greatest variability of phosphorus fractions occurred in the sediments from station 8 (Table 3.13.), though station 4 sediments also had a relatively wide range of phosphorus values. Variations can be attributed, firstly to small scale spatial heterogeneity in sediment type and secondly to the proportion of residual phosphorus which is described above.

Harvey Estuary.

STATION	TOTAL P (µg/g)	ORGANIC P (µg/g)	(%)	APATITE P (µg/g)	(%)	NON APATITE P (µg/g)	(%)
1	676 (386-888)	193 (40-91)	29	148 (13-198)	22	327 (187-390)	49
28	400 (271-583)	100 (80-142)	26	107 (64-147)	28	177 (132-257)	46
29	469 (441-575)	104 (46-145)	23	117 (86-142)	26	223 (159-281)	51
30	180 (113-300)	59 (360-130)	35	38 (13-73)	22	73 (43-107)	43
31	270 (142-797)	64 (30-189)	26	62 (32-159)	25	122 (56-395)	49
37	477 (221-777)	105 (50-176)	24	120 (40-194)	27	213 (126-402)	49
P59	545 (179-885)	113 (31-240)	20	156 (97-253)	28	283 (109-493)	52

Table 3.14. Sediment Phosphorus Fractions from the Harvey Estuary (Mean, Range and percentage of Total P, n=6).

The highest concentration of sediment phosphorus occurred at station 1 with high concentrations in all fractions compared to the other sites (Table 3.14.). Sediment phosphorus concentrations were lowest in the sediment from stations 30.

The highest proportions of organic phosphorus occurred in the sediments from stations 1 and 30. Apatite phosphorus comprised 22% to 28% of the total phosphorus fraction in the sediments while the proportion of non apatite phosphorus ranged from 43% in the sediments at station 30 to 52% in the sediments from station P59. The range in concentration of total phosphorus can be attributed to small scale spatial heterogeneity in these sediments.

Swan-Canning Estuary.

STATION	TOTAL P (µg/g)	ORGANIC P (µg/g)	(%)	APATITE P (µg/g)	(%)	NON APATITE P (µg/g)	(%)
5	1013 (473-2136)	183 (20-648)	18	278 (84-1011)	28	548 (470-776)	54
9	1689 (1489-3082)	174 (28-1067)	10	437 (177-1061)	24	1221 (514-1758)	66
13	892 (566-1275)	164 (36-457)	17	289 (201-441)	29	532 (314-944)	54
14A	211 (126-328)	69 (33-101)	35	49 (20-83)	25	82 (51-123)	41
16	696 (540-1019)	155 (47-236)	20	228 (104-330)	29	391 (217-737)	52
23A	761 (530-1597)	122 (24-278)	15	258 (118-360)	31	448 (249-789)	54

Table 3.15. Sediment Phosphorus Fractions from the Swan-Canning Estuary (Mean, Range and percentage of Total P, n=12).

The total phosphorus concentration in the Swan-Canning sediments ranged from 211µg/g to 1689µg/g (Table 3.15).

The proportion of organic phosphorus in the sediments showed great variability, ranging from 10% to 35%. Apatite phosphorus was relatively constant, ranging from 24% to 31%. The levels of non apatite phosphorus were higher than those in the sediments from Peel Inlet and Harvey Estuary, ranging from 41% at station 14A to 66% at station 9. The proportions of non apatite, and consequently, total phosphorus are related to the iron and aluminum compounds comprising the clay particles with the high W/D ratios, found at the deeper sites like station 9.

Variations result from spatial heterogeneity, particularly associated with dramatic changes in depth over a small area, for example at stations 16 and 9.

Leschenault Inlet.

All three sites in the Leschenault Inlet had similar concentrations of sediment phosphorus (Table 3.16.). The sediments from station 3 showed the greatest variation in phosphorus fractions, attributable to changes of depth at that site.

STATION	TOTAL P (µg/g)	ORGANIC P (µg/g)	(%)	APATITE P (µg/g)	(%)	NON APATITE P (µg/g)	(%)
1	389 (283-379)	74 (39-151)	20	144 (55-98)	38	158 (57-202)	42
3	313 (211-617)	97 (39-142)	34	81 (53-231)	28	110 (55-191)	38
27	290 (200-420)	59 (26-97)	22	124 (30-218)	46	85 (23-216)	32

Table 3.16. Sediment Phosphorus Fractions from Leschenault Inlet (Mean, Range and percentage of Total P, n=12).

The proportion of organic phosphorus in the sediments ranged from 22% to 34%, apatite phosphorus from 28% to 38% and non apatite phosphorus from 32% to 42%.

The proportion of organic phosphorus was high in the sediments from station 3 and similar at stations 1 and 27. The levels of apatite phosphorus were relatively high at all sites but was particularly so from station 27 which had 46% apatite phosphorus. The levels of non apatite phosphorus were correspondingly low with only 32% occurring at station 27, 38% at station 3 and 42% at station 1. These levels were lower than those found in any of the other estuaries.

Comparison Between Estuaries.

The sediments from the Swan-Canning Estuary had a higher phosphorus concentration than those from the other three systems. The exception was the sediment collected from station 14A in which had also shown different physical sediment characteristics related to its shallow depth and larger grain size. The sediment phosphorus fractions in the Harvey Estuary also showed great variability which was related to the range of physical characteristics in the sediments sampled for this survey. As with previous sediment characteristics, the sediments from the Peel and Leschenault Inlets did not exhibit the same range in sediment phosphorus concentrations; the sediments were more homogeneous at sites sampled in those systems.

The proportion of the different fractions in the sediments differed between systems. The sediments from Harvey Estuary and the Swan-Canning Estuary comprised predominantly non apatite phosphorus while the phosphorus of sediments from Peel Inlet, although consisting predominantly of the non apatite form, contained higher proportions of organic and apatite phosphorus. The sediments from Leschenault Inlet contained a higher proportion of apatite phosphorus than did sediments from the other systems.

4. DISCUSSION

4.1. Physical Characteristics

The results have shown a wide range of sediment physical characteristics between both the systems and the sampling sites. However, a strong relationship has been established between the W/D ratio of the sediment and the other physical characteristics. The relationship between W/D ratio and water content was highly significant (r^2=0.999) (Table 4.1). The relationship between W/D ratio and grain size was determined because fine particles are known to bind phosphorus in sediment; the relationship between the W/D ratio and both the median grain size and percentage of particles finer than 75um was linear and statistically significant (r^2=0.743 and r^2=0.765) (Table 4.2, Figure 4.1). The W/D ratio was therefore adopted as an indicator of sediment type.

CORRELATION WITH W/D RATIO	% H2O	(r^2)
PEEL INLET	0.999	(n=30)
HARVEY ESTUARY	1.000	(n=42)
SWAN-CANNING ESTUARY	1.000	(n=72)
LESCHENAULT INLET	0.998	(n=36)
ALL ESTUARIES	0.999	(n=180)

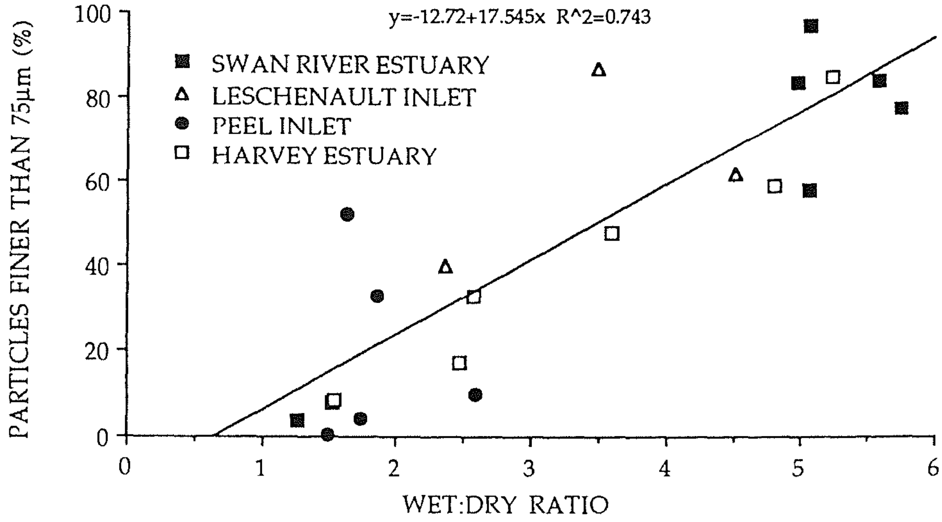
Table 4.1. W/D Ratio versus Water Content (r^2>0.3014, α=0.01)

The grain size characteristics of the sediments are significant because the observed phosphorus distribution in the sediments is related to the particle size distribution, i.e. the Fe and Al-bound phosphorus is associated with the finer sediment fractions while the Ca-bound P is found in the coarser fractions (Frink 1969). Viner (1988) showed a relationship between phosphorus and the surface area of sediment particles. Clay particles which have a high surface area to volume ratio contain a higher concentration of sorbed P which, in turn, is proportional to the concentration of extractable iron.

CORRELATION WITH W/D RATIO	MEDIAN GRAIN SIZE (r^2)	PARTICLES FINER THAN 75 µm (r^2)
ALL ESTUARIES	0.765 (n=21)	0.743 (n=21)

Table 4.2. W/D Ratio versus Grain Size Data (r^2>0.3014, α=0.01)

The physical data disclosed differences between sampling stations within each estuary and between the estuarine systems themselves. This pattern can be partly explained by the morphometric characteristics of the systems. The sediments in Leschenault Inlet and Harvey Estuary are more diverse than the other two systems, comprising sands, silts and fine silts. Nevertheless, sites chosen in Leschenault Inlet were all in the centre of the system and were of similar sediment composition, and so there was little variation in the data from this system. The sampling sites in Harvey a.



b.

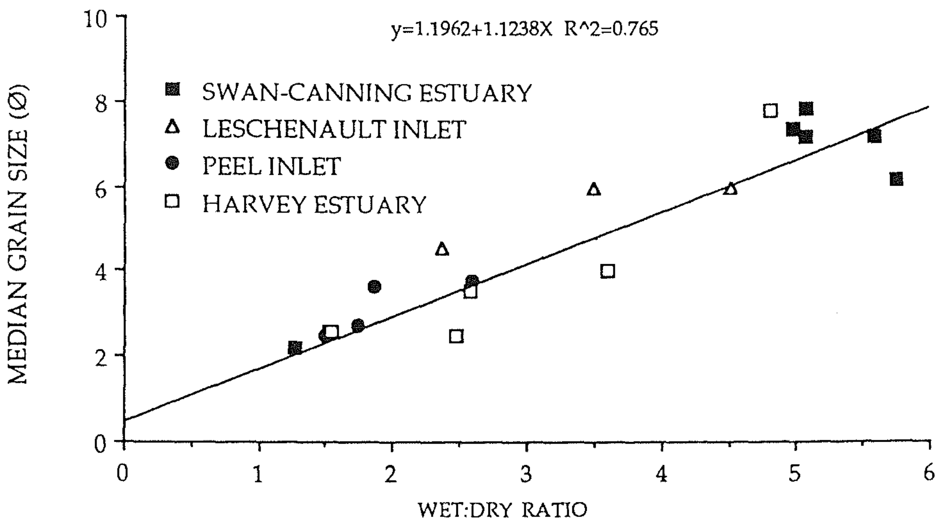


Figure 4.1: W/D Ratio versus: a. Particles Finer than 75µm; b. W/D Ratio versus Median Grain Size (Ø) ($r^2 > 0.3014$, $p<0.01$).

Estuary encompassed all the sediment types and the range of physical sediment characteristics indicated in the results reflect this.

Peel Inlet is more sheltered than Harvey Estuary, and as a result of the smaller fetch in Peel Inlet, there is less mixing, resuspension and redistribution of sediment particles. The sediments in Peel Inlet are therefore more uniform with differences in sediment characteristics attributed to depth, i.e. the differences occur between the central and marginal sediments, and the degraded algal bed (Station 8).

The sediments in the Swan-Canning Estuary are more affected by the range in depths and turbulence at the sampling stations. As a result the sediments are more influenced by the effects of scouring and the resuspension of fine sediments washed into the system during periods of high rainfall. Frink (1969) has described the importance of depth in the distribution of clay particles, organic matter and total phosphorus and this is reflected in the results from the Swan-Canning Estuary where the finest particles with the highest concentrations of total phosphorus were found at the riverine stations, which also had the greatest depth.

4.2. Chemical Characteristics.

The results indicated that the highest levels of iron and aluminum occurred in the Swan-Canning Estuary, particularly at stations 9 and 16 which were the deepest sites. The possible source of the iron and aluminium is the weathering in the catchment, as in the catchment soils are rich in aluminium and iron. The heavy winter rainfall washes the fine aluminosilicate clays into the river and these settle into the deeper regions represented in this study by the riverine sites at stations 5 and 9 and the more estuarine site at station 16.

CORRELATION WITH W/D RATIO	%Al (r^2)	%Fe (r^2)	%Ca (r^2)	%CaCO3 (r^2)
ALL ESTUARIES (n=21)	0.843	0.892	0.425	0.005

Table 4.3. W/D Ratio versus Chemistry Centre Data ($r^2>0.3014$, $\alpha=0.01$).

Sediments at two stations in the Harvey Estuary (1 and P59) also showed relatively high levels of iron and aluminium, and these sediments also had high W/D ratios and a high proportion of fine particles. Clearly the iron and aluminium that is present in sediments of Harvey Estuary, albeit at lower concentrations than in the Swan-Canning Estuary, are associated with the finer clay particles.

Accumulations of iron and aluminium in Peel Inlet sediments was lower than in the other two systems. A strong correlation exists between grain size (as represented by W/D ratio) and the presence of aluminium and iron (r2=0.892) (Table 4.3, Figure 4.2). Peel Inlet sediments had lower W/D ratios than Harvey Estuary or Swan-Canning Estuary and therefore, predictably,

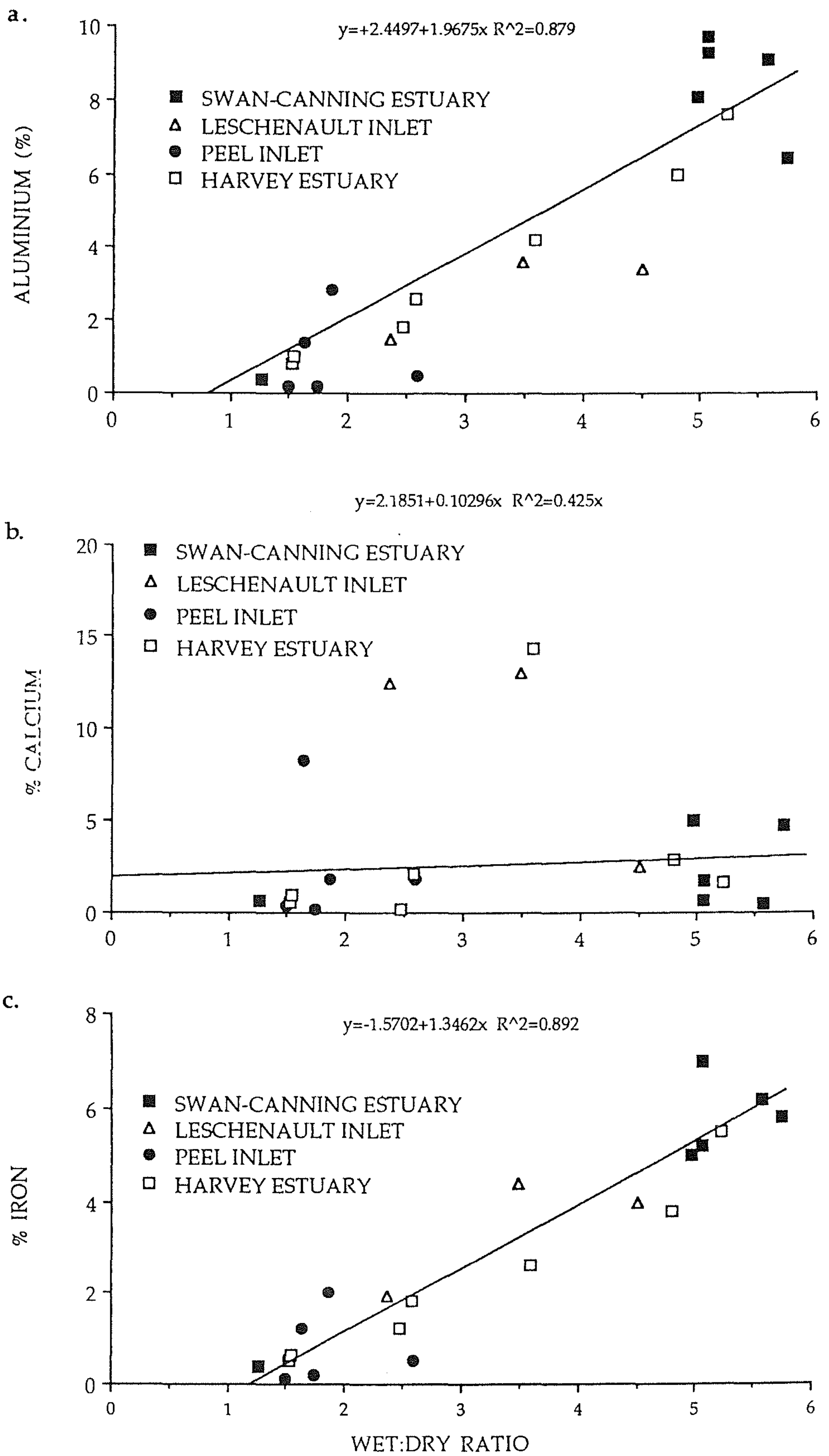


Figure 4.2: W/D Ratio versus: a. Aluminium Content; b. Calcium Content; c. Iron Content (%) ($r^2 > 0.3014$, $p < 0.01$).

had lower levels of iron and aluminium. The levels of iron and aluminium in the sediments from Leschenault Inlet were within the expected range based on the relationships between particle size and iron and aluminum content from the other systems. These data indicate that the Harvey and Swan-Canning estuaries have the greatest potential for adsorption of phosphorus and subsequent release.

Calcium also binds with phosphorus but phosphorus release from calcium or other apatite molecules is not as significant as from iron or aluminium. Indeed, apatite phosphorus is considered to be only sparingly available to algae, in contrast to other phosphorus fractions (Hegemann et al 1983, Rosich and Cullen 1980). CaCO3 is said to be inversely proportional to total and inorganic phosphorus concentrations and plays a much lesser role in controlling phosphorus release in natural systems than does iron (Williams et al 1971). Sediments with high levels of calcium carbonate tend to release very little phosphorus (Petterson 1986) and addition of calcium carbonate has been used to control phosphorus release in lakes. Unlike iron and aluminium complexes, calcium complexes have been found to be associated with the coarse grained sediments (Frink 1969).

Table 4.3 and Figure 4.2. indicate that there is no clear relationship between the W/D ratio and the presence of calcium in the sediment, and no relationship between W/D ratio and the presence of calcium carbonate. However, it appears that sediments from Leschenault Inlet do have a higher calcium content than those from the other systems, and this might reduce the potential for phosphorus release from these sediments. It is likely that the higher calcium content in the sediments from Leschenault Inlet and some of the stations in Peel Inlet (4, 7, 8) and Harvey Estuary (1, 28, 29) result from the proximity of these sediments to the inflow of marine water into the respective estuaries.

Organic matter has been found to depress phosphate adsorption, the ability of silts to adsorb phosphate being directly related to the ratio of their iron content to their organic matter content (Jitts 1959). Klapwijk *et al* (1982) also found a negative correlation between the presence of organic matter and the concentration of algal-available phosphorus. However, Table 4.4 and Figure 4.3 indicate a strong relationship between the W/D ratio of the sediment and the presence of organic matter, suggesting that the significance of organic matter is its relation to sediment grain size.

CORRELATION WITH W/D RATIO	% ORGANIC MATTER (r2)
PEEL INLET	0.825 (n=30)
HARVEY ESTUARY	0.858 (n=42)
SWAN-CANNING ESTUARY	0.855 (n=72)
LESCHENAULT INLET	0.781 (n=36)
ALL ESTUARIES	0.805 (n=180)

Table 4.4. W/D Ratio versus % Organic Matter ($r^2 > 0.3014$, $\alpha=0.01$).

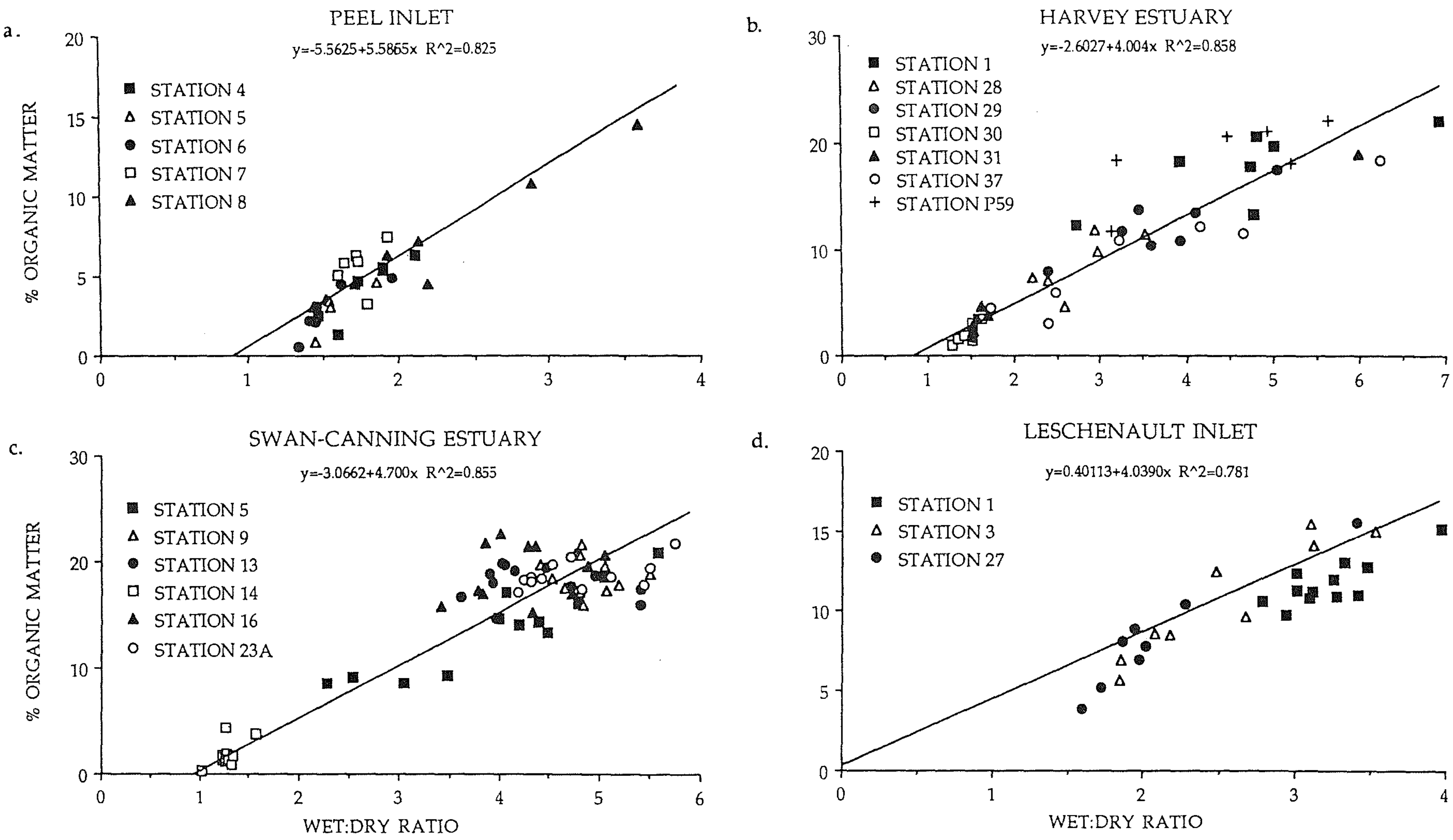


Figure 4.3: W/D Ratio versus Organic Matter Content (%) a. Peel Inlet, b. Harvey Estuary, c. Swan-Canning Estuary, d. Leschenault Inlet ($r^2 > 0.3014$, $p < 0.01$).

4.3. Sediment Phosphorus Content

The highest concentrations, of all the phosphorus fractions, have occurred in the sediments of the Swan-Canning Estuary, most particularly in the upper river reaches at stations 5 and 9. The sediments from station 9 contained the highest concentration of phosphorus but more importantly, they had a high proportion of non apatite phosphorus (66%), compared to the other fractions. The ratio of non-apatite to apatite phosphorus in Peel Inlet and Harvey Estuary sediments was found to be 2:1 (Lukatelich 1987) but this ratio was close to 3:1 in sediments from station 9. The non-apatite to apatite ratio was 2:1 or slightly less for the remaining sediments. Non-apatite phosphorus is considered to be the fraction available to algae and it is therefore significant that this fraction is higher in the sediments from the Swan-Canning sediments than those of either Peel Inlet or Harvey Estuary, where high phosphorus release has been documented (Lukatelich 1987). There is a high concentration of total phosphorus in the Swan-Canning sediments, up to 66% of which is potentially available to algae.

The sediments from Peel Inlet had relatively low levels of sediment phosphorus and correspondingly low W/D ratios. Some of the sediments from Harvey Estuary also carried relatively high internal phosphorus concentrations but these ranged from a low 180 µg/g at station 30 to concentrations of 676 µg/g at station 1. These results highlight the potential for phosphorus release in the Swan-Canning Estuary where the internal total phosphorus concentration in the sediments was as high as 1689µg/g, and as noted above, had a high proportion of non-apatite phosphorus. The proportion of apatite phosphorus was higher than expected giving a ratio of non-apatite to apatite phosphorus of less than 2:1 in Peel Inlet with the highest proportion of apatite phosphorus (35%) occurring in the sediments from station 7 which also contained the highest levels of calcium (8.2%).

It was the percentage of organic phosphorus that showed the greatest variation in the sediments from the Swan-Canning Estuary, ranging from 10% to 35%. It is difficult to interpret the differences in organic phosphorus concentrations because this fraction is determined by difference and not direct chemical analysis. It is therefore more appropriate to concentrate on the differences in the other fractions.

The concentrations of total phosphorus in sediments from Leschenault were relatively low. The percentage of organic phosphorus ranged from 20% to 34%. The proportion of apatite to non-apatite phosphorus was extremely high in comparison to the sediments from the other three systems and the percentage of apatite phosphorus in these sediments ranged from 28 to 46%. The sediments from stations 1 and 27 also contained the highest levels of calcium in any of the estuaries. The concentration of non-apatite phosphorus was correspondingly low and therefore the potential for phosphorus release from these sediments is lower than in those from the Swan-Canning Estuary, Harvey Estuary and the majority of the sediments from Peel Inlet.

There is a strong correlation between W/D ratio and the concentration of total phosphorus for the majority of the estuarine sediments ($r^2=0.634$); exceptions are those from station 9 in the Swan-Canning Estuary and sediments from Leschenault Inlet ($r^2=0.634$) (Table 4.5, Figure 4.4). Most of the variability in total phosphorus can be accounted for by the variability in sediment type as indicated by W/D ratio. This suggests that total phosphorus can be predicted from the W/D with an average of 63% accuracy. The implication is that where points fall outside the predicted limits of this linear relationship, they can be taken as evidence that the sediment is carrying a higher or lower phosphorus loading than its grain type would suggest, perhaps as a result of anthropogenic input or major changes in the catchment soil type. Conversely, any results depicting concentrations of sediments phosphorus should be normalised using grain size. A higher-than-predicted internal phosphorus loading of a sediment is a result of anthropogenic input and not a function of the sorbing ability of the sediment, regardless of its physical characteristics. Station 9, in the Swan River is adjacent to a major storm water drain and to the Belmont tip. The high internal loading of these sediments may result from anthropogenic input through phosphorus leaching from the tip site and from run-off from the storm-water drain.

Correlation With W/D Ratio	Total P (μg/g)	Organic P (μg/g)	Apatite P (μg/g)	Non-Apatite P (μg/g)	n
Peel Inlet	0.621	0.106	0.453	0.510	30
Harvey Estuary	0.890	0.481	0.648	0.859	42
Swan-Canning Estuary	0.571	0.122	0.493	0.469	72
Leschenault Inlet	0.140	0.190	0.006	0.040	36
All Estuaries	0.634	0.252	0.478	0.552	180

Table 4.5. W/D Ratio versus Sediment Phosphorus Content. ($r^2 > 0.3014$, $\alpha=0.01$).

The strong relationship between sediment type, as represented by the W/D ratio, and concentration of phosphorus in the sediment suggests that if the appropriate physical sediment data are available i.e. either grain size or W/D ratio, a prediction of phosphorus concentration within the sediment can be made. To test this theory data collected from three other south western estuaries (the Wilson Inlet at Denmark and Princess Royal Harbour and Oyster Harbour at Albany) were added to the existing W/D versus total phosphorus plot (Figure 4.5.). The relationship was essentially the same ($r^2=0.654$).

The implication of this relationship is that high frequency monitoring of phosphorus fractions of the sediments at these stations will not reveal anything new about the relationships between the sediments and the system. The sediment characteristics are less variable than those of the overlying water body (Ostrofsky 1987) and therefore high frequency monitoring of the same sites are unlikely to highlight changes in the estuary that would lead to an increase or decrease in the eutrophication of the system.

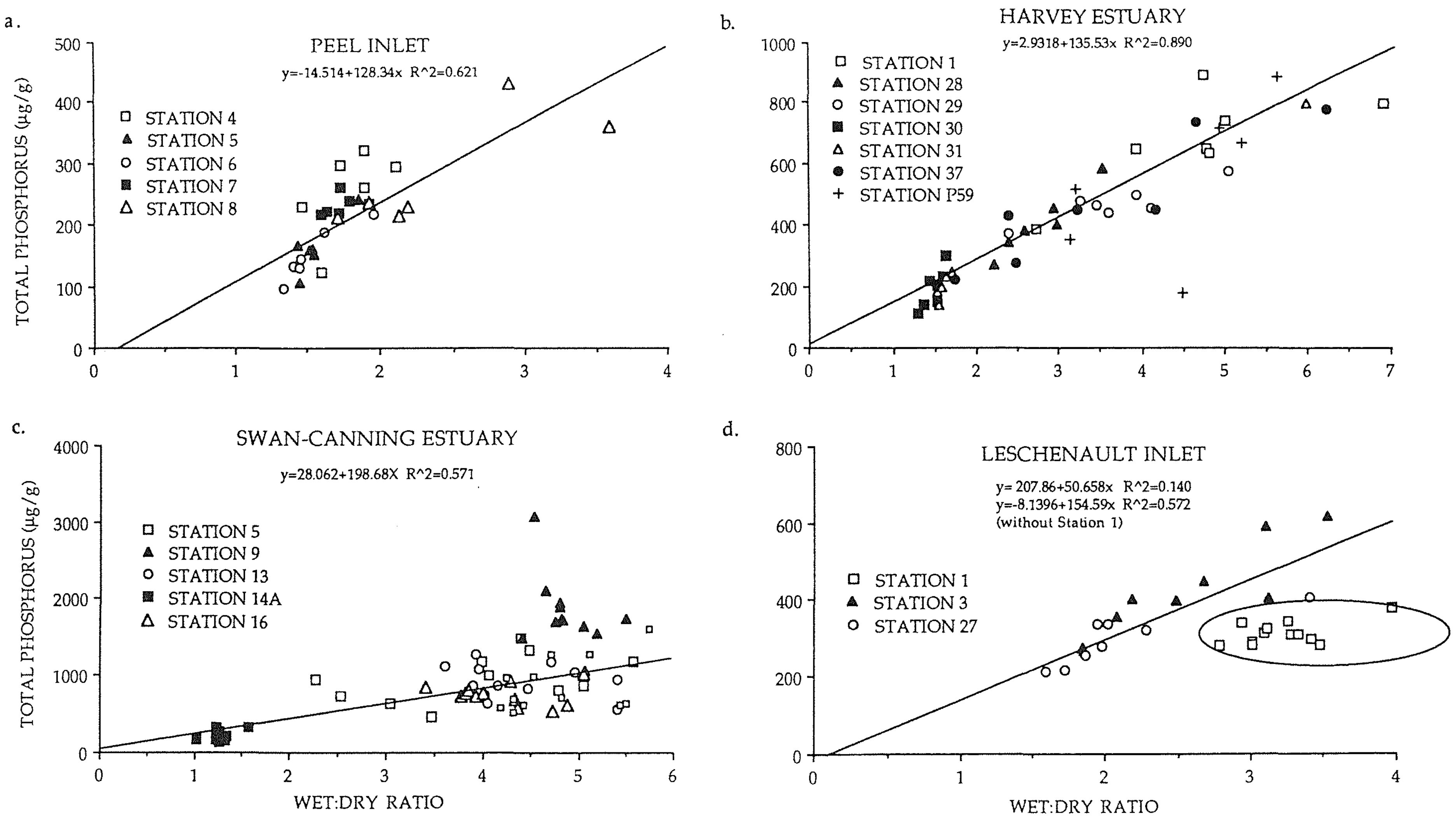


Figure 4.4: W/D Ratio versus Total Phosphorus Content (µg/g) a. Peel Inlet, b. Harvey Estuary, c. Swan-Canning Estuary, d. Leschenault Inlet ($r^2 > 0.3014$, $p < 0.01$).

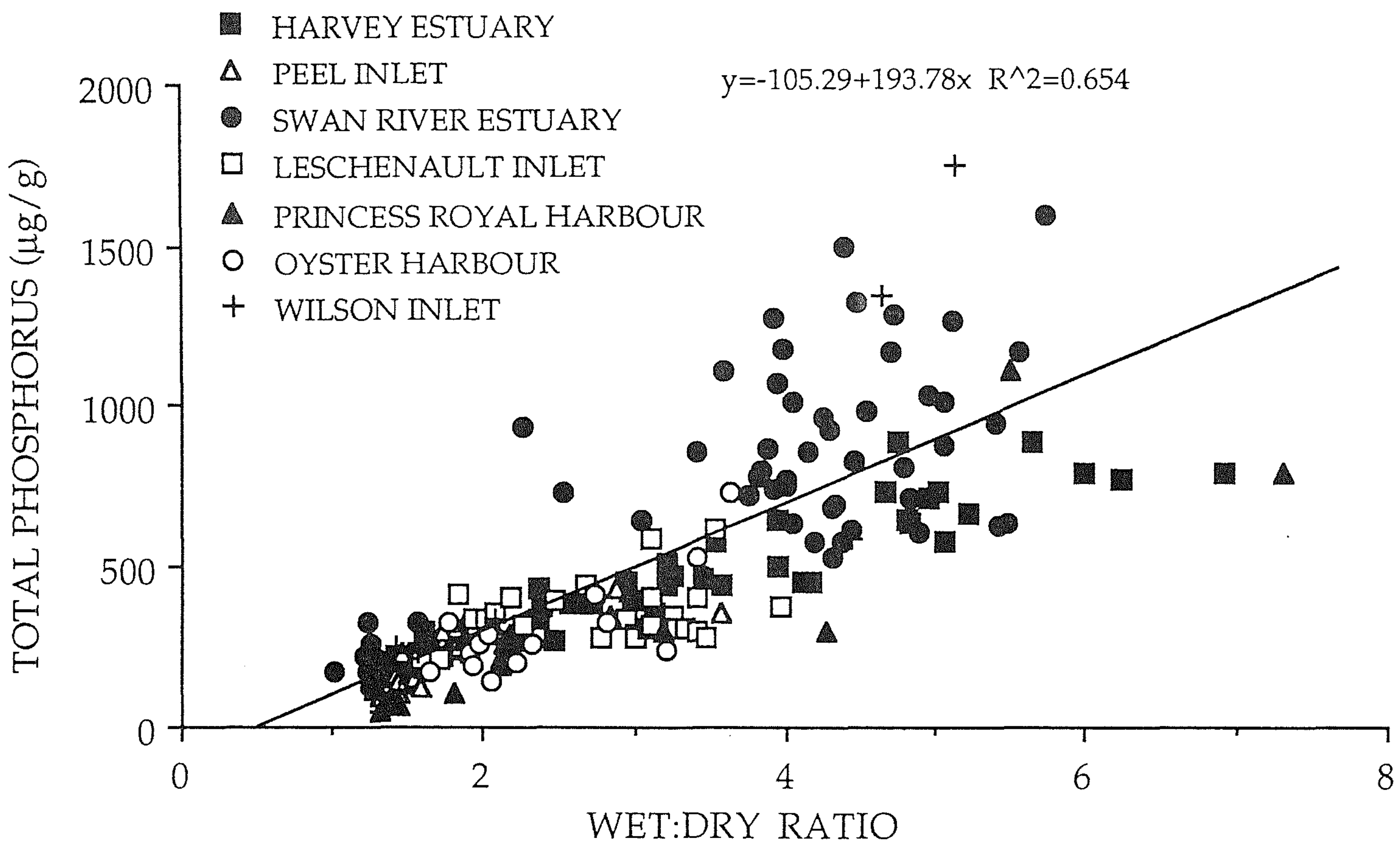


Figure 4.5: W/D Ratio versus Total Phosphorus Concentration (µg/g) for seven Southwest Estuaries ($r^2 > 0.3014$, $p < 0.01$).

There is no evidence for a significant correlation between the internal phosphorus loading of the sediment and the trophic state of the overlying water body (Williams and May 1972, Lukatelich 1987).

The establishment of a relationship between sediment type and internal total phosphorus loading provides a basis for predicting the nutrient status of the sediments in estuaries, more generally, in the Southwest of Australia. The hypothesis needs to be tested further particularly for sediments from pristine oligotrophic estuaries. Once the relationship has been established for a wider range of sediments it will be possible to use it to pinpoint possible areas with anthropogenic input. By collecting sediments and carrying out simple analyses for W/D ratio and total phosphorus concentration we can use the existing relationship to determine whether of not a sediment contains the phosphorus concentration we would predict from our curve or whether the sediment phosphorus concentration is higher than we would predict. By pin-pointing these areas, it will be possible to look for sediments with the potential for high phosphorus release.

There is no correlation between W/D ratio and the concentration of organic phosphorus in the sediment (r^2=0.252) (Table 4.5., Figure 4.6.). The W/D ratio does not account for as much variability in the other phosphorus fractions as it does for total phosphorus and therefore it will still be necessary to measure these analytically but at a lower frequency than that used for the water column because the sediment phosphorus parameters are less variable than those of the overlying water.

In summary, this survey has shown that the differences in the physical and chemical characteristics of the sediments result from the geomorphology of the estuaries and their catchments. The choice of sites in each of the estuaries has highlighted the similarities between estuaries and the spatial heterogeneity of sediments within estuaries. The variation in chemical parameters correlates strongly with sediment type which was represented, in this survey, as W/D ratio.

Although there was no clear relationship between sediment phosphorus content and the trophic state of the estuaries, the potential for phosphorus release from the sediments has been highlighted, particularly in the sediments from Swan-Canning Estuary where the non-apatite phosphorus fraction was greater than 50%.

A monitoring programme is currently being carried out, at Murdoch University for the Waterways Commission, to observe phosphorus release from intact cores taken from each of the four systems on a monthly basis and the results will be published in a subsequent report.

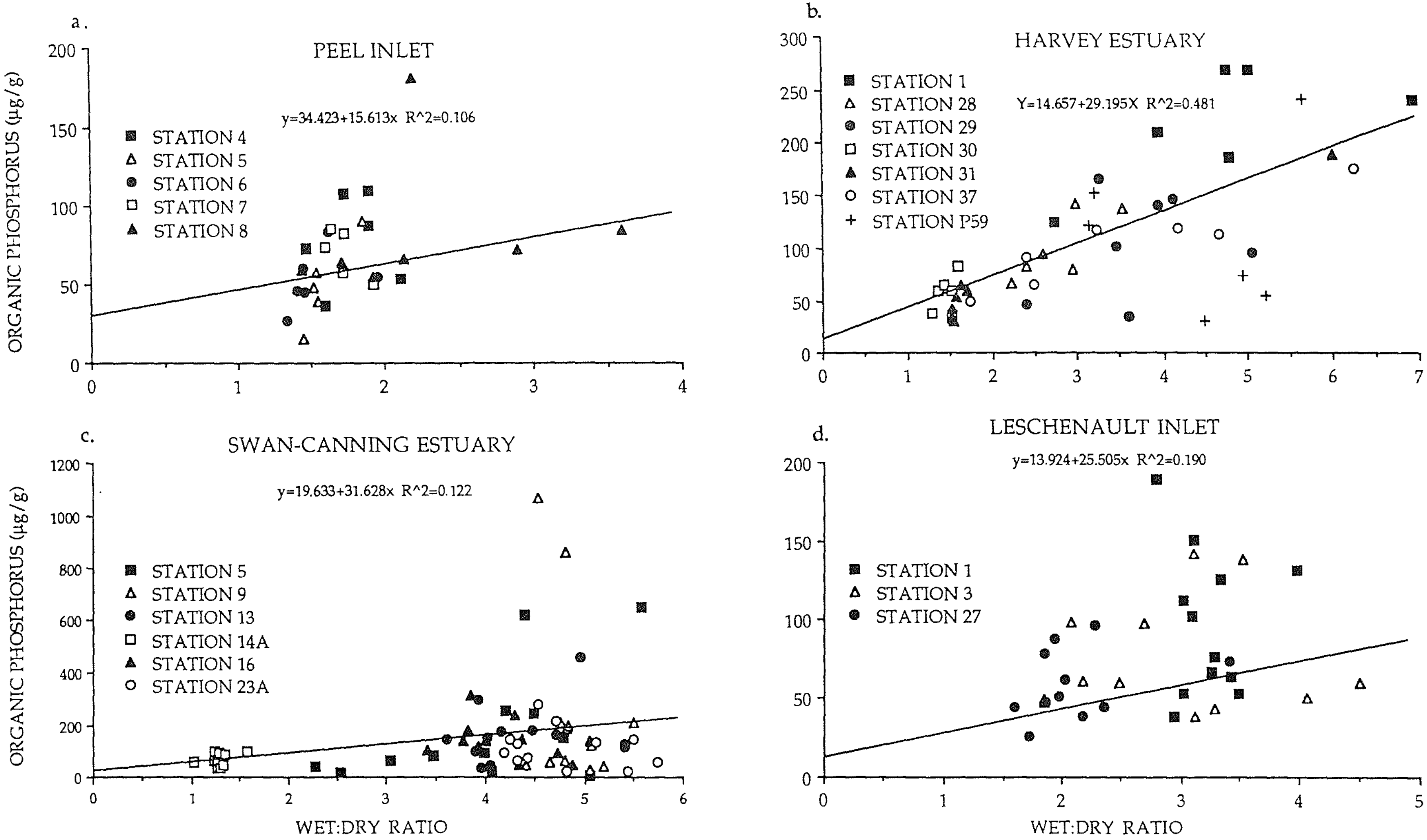


Figure 4.6: W/D Ratio versus Organic Phosphorus Concentration (µg/g) a. Peel Inlet, b. Harvey Estuary, c. Swan-Canning Estuary, d. Leschenault Inlet ($r^2 > 0.3014$, $p < 0.01$).

The relationship established between W/D ratio, as an indicator of sediment type, and the total phosphorus concentration of the sediments will be investigated further in a survey of the sediments from the Collie, Serpentine and Murray Rivers, in addition to several sites in and around Peel Inlet. Analyses will be carried out to determine W/D ratio, grain size and the total phosphorus concentration of these sediments; the results will also be published in a subsequent report.

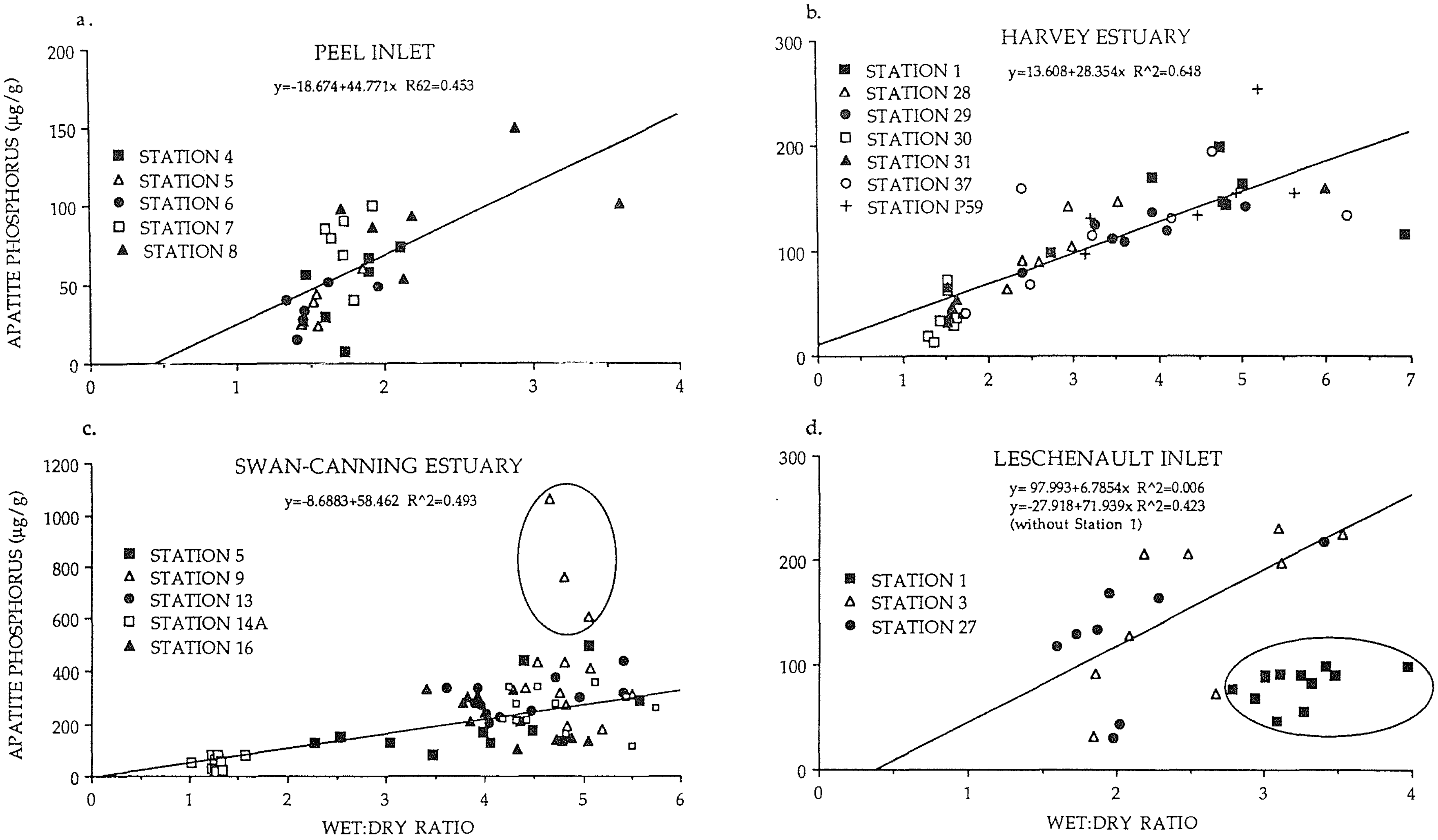


Figure 4.7: W/D Ratio versus Apatite Phosphorus Concentration (µg/g) a. Peel Inlet, b. Harvey Estuary, c. Swan-Canning Estuary, d. Leschenault Inlet ($r^2 > 0.3014$, $p < 0.01$).

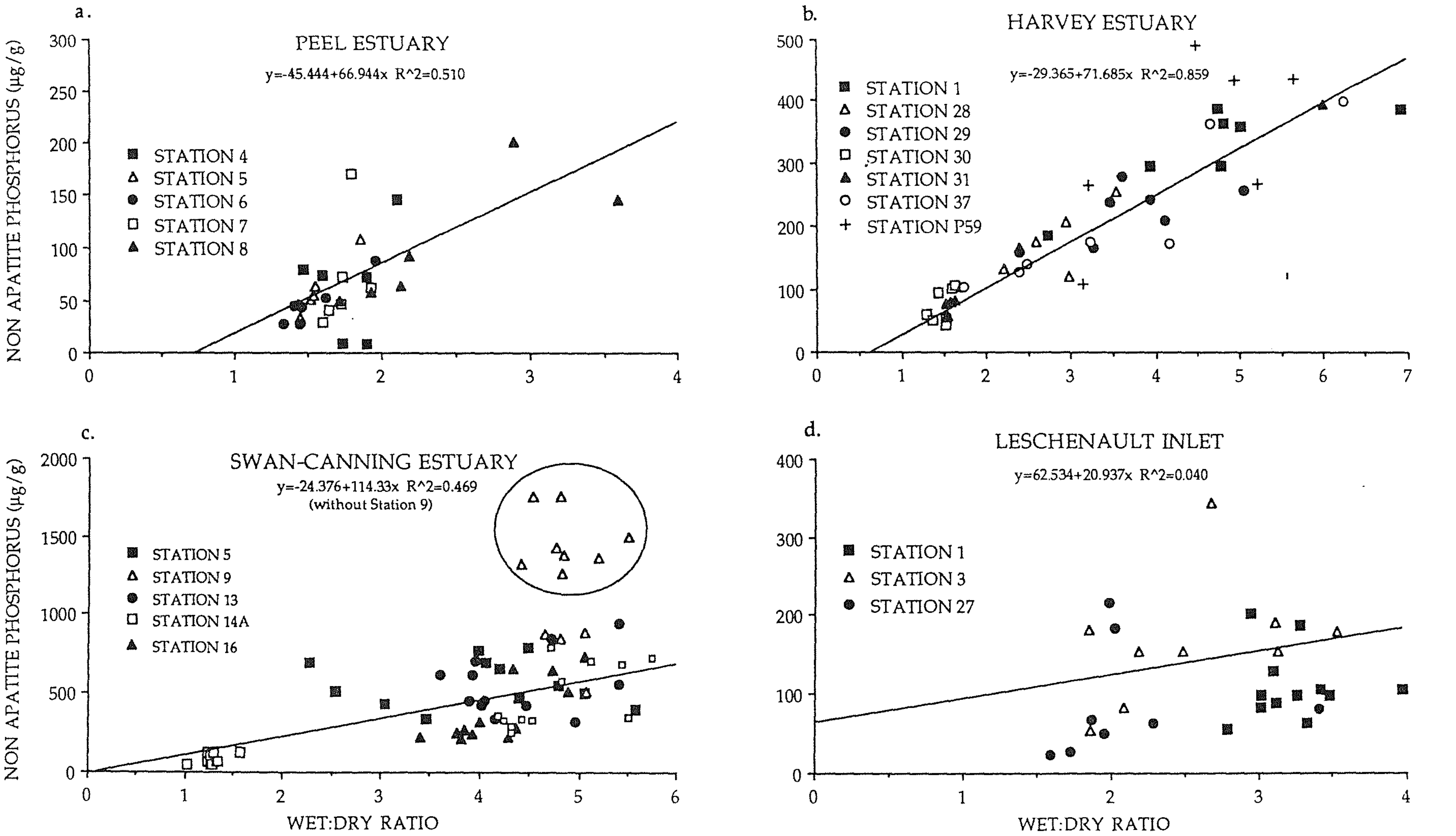


Figure 4.8: W/D Ratio versus Non-apatite Phosphorus Concentration (µg/g) a. Peel Inlet, Harvey Estuary, c. Swan-Canning Estuary, Leschenault Inlet ($r^2 > 0.3014$, $p < 0.01$).

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References.

Bates, M.H. and Neafus, N.J.E. (1980) Phosphorus release from sediments from Lake Carl Blackwell, Oklahoma. Water Research **14 (10)**, 1477-1481

Bostrom, B. and Petterson, K. (1982) Different patterns of phosphorus release from lake sediments in laboratory experiments. Hydrobiologia **92**, 415-429

Bostrom, B., Ahlgren, I. and Bell, R. (1985) Internal nutrient loading in a eutrophic lake, reflected in seasonal variations of some sediment parameters. Verh. Int. Verein. Limnol. **22**, 3335-3339

Coey, J.M.D., D.W. Schindler and F. Weber (1974) Iron compounds in lake sediments. Canadian Journal of Earth Science **11**, 1489-1493

Davis, M.B. and Ford, M.S. (1982) 'Sediment Focusing in Mirror Lake, New Hampshire'. Limnology and Oceanography **27**, 137-150

Evans, R.P. and Rizler, F.H. ('Measurement of whole lake sediment accumulation and phosphorus retention using lead-210 dating'. Canadian Journal of Fisheries and Aquatic Research **37**, 817-822

Forsberg, C. (1987) Importance of sediments in understanding nutrient cyclings in lakes. (Paper presented at the 46th International symposium Interactions between sediments and water, Melbourne, Australia.) 22pp

Frink, C.R. (1969) Fractionation of phosphorus in lake sediments analytical evaluation. Soil Science Society of America Proceedings **33** , 326-328

Frink, C.R. (1969) Eutrophic lake sediments Soil Science Society of America Proceedings **33**, 369-372

Frink, C.R. (1969) Chemical and mineralogical characteristics of eutrophic lake sediments. Soil Science Society of America Proceedings pp 369-372

Gachter,R. (1987) Lake restoration. Why oxygenation and artificial mixing cannot substitute for a decrease in the external phosphorus loading. Schweizerische Zeittschrift fuer Hydrologie **49 (2)**, 170-185

Gillion, R.J. (1984) Relationships between water quality and phosphorus concentrations for Puget Sound region lakes. Water Research. **20(3)**, 435-442

Grobler, D.C. and Davies, E. (1981) Sediments as a source of phosphate : A study of 38 inpoundments. Water (South Africa) **7(1)**, p 54

Hallberg, R.O., Bagander, L.E., Engwall, A.G., Lindstrom, H., Oden, S. and Schippel, F.A. (1973) The chemical microbiological dynamics of the sediment-water interface. Contr. Asko Lab., **2** , 1-117

Hegemann, D.A., Johnson, A.H. and Keenan, J.D. (1983) Determination of algal-available phosphorus on soil and sediment : A review and analysis. Journal of Environmental Quality **12 (1)**, 12-16

Holdren, G.C. and Armstrong, D.E. (1986) Interstitial ion concentrations as an indicator of phosphorus release and mineral formation in lake sediments in: P.G. Sly (ed), Sediments and Water Interactions, Springer-verlag, N.Y., Chapter 12, 133-147

Jitts, H.R. (1959) The adsorption of phosphate by estuarine bottom deposits. Australian Journal of Marine and Freshwater Research **10** , 7-21

Klapwijk, A. and Snodgrass, W.J. (1981) Model for nitrification-denitrification and oxygen demand in lake sediments. Manuscript, Dept. Chemical Engineering, McMaster University, Hamilton, Ontario, 30pp.

Klapwijk, A. and Snodgrass, W.J. (1982) Experimental measurement of sediment nitrification and denitriification in Hamilton Harbour, Canada. In: Sly, P.G. (ed.), Proceedings 2nd Int. Sediment Freshwater Interaction Symp., June 1981, Kingston, Ontario

Klapwijk, A. and Snodgrass, W.J. (1986) Lake oxygen Model 2: Simulation of nitrification and denitrification in Hamilton Harbor using laboratory data, in: P.G. Sly (ed), Sediments and Water Interactions, Springer-Verlag, N.Y., Chapter 22, 251-264

Klapwijk, A. and Snodgrass, W.J. (1986) Lake oxygen Model 3: simulation of ammonia, nitrate and oxygen in Hamilton Harbor (19777-1978), in: P.G. Sly (ed), Sediments and Water Interactions, Springer-Verlag, N.Y., Chapter 23, 265-288

Klapwijk, S.P. and Bruning, C. (1986) Available phosphorus in the sediments of eight lakes in the Netherlands in: P.G. Sly (ed), Sediments and Water Interactions, Springer-Verlag, N.Y., Chapter 34, 391-397

Klapwijk, S.P., Kroon, J.M.W. and Meijer, M.L. (1981) Available phosphorus in lake sediments in The Netherlands. In : P. G. Sly (ed.) Sediment Freshwater Interaction. Developments in Hydrobiology, 491-500 Dr W Junk, The Hague.

Li, W.C., Armstrong, D.E., Williams, J.D., Harris, R.F. and Syers, J.K. (1972) Rate and extent of inorganic phosphate exchange in lake sediments. Soil Sciience Society of America Proceedings **36**, 279-285

Lukatelich, R.J. (1987) Nutrients and Phytoplankton in the Peel-Harvey Estuarine System, Western Australia. Ph.D. Thesis University of Western Australia.

Marsden, M.L. (1989) Lake restoration by reducing external phosphorus loading: the influence of sediment phosphorus release. Freshwater Biology **21**, 139-162

Mortimer, C.H. (1949) Underwater "soils": A review of lake sediments. Journal of Soil Science **1**, 63-73

Ostofsky, M.L. (1987) Phosphorus species in the surficial sediments of lakes of Eastern North America. Canadian Journal of Fishisheries and Aquatic Science **44**, 960-966

Rosich, R.S. and Cullen P. (1980) Lake sediments: algal availability of Lake Burley Griffin sediment phosphorus. In: Biogeochemistry of Ancient and Modern Enviroments (eds) Trudinger P.A. and Whaller M.R. Australian Academy of Science, Canberra, Australia, 117 - 122

Strickland, J.D.H. and Parsons, T.R. (1972) A Practical handbook of seawater analysis. 2nd edition. Bulletin of the Fisheries Research Board Canada

Thurlow, B.H., Chambers, J. and Klemm, V.V. (1986) Swan-Canning Estuarine System Environment, Use and the Future. Waterways Commission, Perth, W.A. Report No. 6.

Viner, A.B. (1988) Phosphorus on suspensoids from the Tongariro River (North Island, New Zealand) and its potential availability for algal growth. Archives fur Hydrobiologie **111(4)**, 481-489

Williams, J.D.H., Jaquet, J.M. and Thomas, R.L. (1976) Forms of phosphorus in the surficial sediments of Lake Erie. Journal for the Fisheries Research Board Canada **33**, 413-429

Williams, J.D.H., Murphy, T.P. and Mayer, T. (1976) Rates of accumulation of phosphorus forms in Lake Erie sediments. Journal for the Fisheries Research Board Canada **33**, 430-439

Williams, J.D.H., Syers, J.K., Armstrong, D.E. and Harris, R.F. (1971) Characterization of inorganic phosphate in noncalcareous lake sediments. Soil Science Society America Proceeding **35**, 556-561

Williams, J.D.H., Syers, J.K., Harris, R.F. and Armstrong, D.E. (1971) Fractionaction of inorganic phosphate in calcareous lake sediments. Soil Science Society of America Proceedings **35**, 250-255

Williams, J.D.H., Syers, J.K., Shukla, S.S., Harris, R.F. and Armstrong, D.E. (1971c) Levels of inorganic and total phosphorus in lake sediments as related to other sediment parameters. Environmental Science and Technology **5**, 1113-1120