SEDIMENTATION SURVEYS OF ADELAIDE'S COASTAL REEFS, PART 1 (WINTER AND SUMMER):

a report prepared for the Adelaide and Mount Lofty Ranges Natural Resources Management Board

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

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EXECUTIVE SUMMARY

This work was commissioned by the Adelaide and Mount Lofty Ranges Natural Resources Management Board to determine sedimentation rates along Adelaide's coastal reefs after major rainfall events, and to provide information on the potential sources of these sediments. For this purpose, sediment traps were deployed at 12 reefs between Semaphore and Aldinga in August and November/December 2007. Sediment samples from potential terrestrial sources were also collected in the same period.

Reef sediments were analysed for nitrogen and phosphorus contents, the stable isotope ratios of carbon and nitrogen, and particle size distributions. Selected samples were also analysed for a series of elements (Al, Ca, Cr, Cu, Fe, K, Mg, Na, Ni, Pb, Sr and Zn). Samples from potential land-based sources were analysed for carbon isotopic composition, particle size distributions and geochemical composition.

Reefs close to the mouth of the Onkaparinga River are subject to the highest rates of sedimentation along the metropolitan coast, with deposition reaching up to 210 g m^{-2} d^{-1}. Fluvial discharges and cliff-face erosion, combined with high energy waves and negligible transport offshore, act to sustain high sedimentation rates for prolonged periods of time (i.e. several weeks) in these near-shore systems. Reefs further south receive inputs of similar terrestrial origin, albeit at rates never exceeding 31 g m^{-2} d^{-1}. In contrast, reefs in the northern section of the metropolitan coast, which are located further offshore than their southern counterparts, have low sedimentation rates (< 10 g m^{-2} d^{-1}) and show no evidence of riverine-derived sedimentation. The Torrens and Patawalonga rivers represent the main conduits of stormwater to this part of the coast, but inputs are likely to remain trapped in the near-shore zone as a consequence of the predominant north-south circulation. Northern reefs are, however, influenced by wastewater/industrial discharges, possibly from the Bolivar and Glenelg wastewater treatment plants, or the Penrice soda factory through the Port River.

1 INTRODUCTION

Reefs provide a unique ecological niche in temperate marine systems, showing high biodiversity and supporting a number of commercial fisheries (O'Hara 2001; Shears and Babcock 2002; Vanderklift and Kendrick 2004). These ecosystems are however, particularly vulnerable to anthropogenic influence, with significant changes in habitat structure and functioning observed as a result of increased human pressure (Roberts et al. 1998; Russell et al. 2005). The reefs along the Adelaide metropolitan coast are no exception, and have shown signs of deterioration over the last few decades (Turner et al. 2007). Increased sediment supply from terrestrial runoff is generally listed as one of the major factors leading to a decline in reef health worldwide (Connell 2005; Balata et al. 2007). Although Adelaide is located in a semi-arid climate where runoff is typically low, its coastal strip has been subject to intense urban and agricultural development, and sediment loads to sea have increased accordingly (Wilkinson 2005; Wilkinson et al. 2005a; Wilkinson et al. 2005b).

The increase in sedimentation in regions affected by human development is accompanied by a change in the geochemical composition, nutritional value, and physical properties of sediments. A number of fingerprinting techniques can be used to assess these changes and to pinpoint likely sources (Walling et al. 1999). Greater rigour and reliability is achieved by analysing several diagnostic properties simultaneously. When enough sample is available, a detailed elemental scan provides a relatively cost- and time-effective approach to building a larger dataset for deriving composite fingerprints. Carbon, nitrogen and phosphorus are also commonly used to this end because their stable isotopic (e.g. $^{13}C/^{12}C$ and $^{15}N/^{14}N$) and molar ratios (e.g. N:P) vary between different biological materials (Ostrom and Fry 1993; Cross et al. 2005).

In coastal sites, organic matter transported with sediments derives from a mixture of terrestrial and marine sources. The uptake of carbon in aquatic plants is limited by diffusion, leading to low selectivity towards the heavy isotope and higher isotopic signatures when compared to terrestrial plants (Ostrom and Fry 1993). Nitrogen is another useful tracer, particularly to track wastewater pollution, as the secondary treatment used in wastewater treatment plants (WWTPs) results in an increase in nitrogen isotopic signatures to much higher values than found naturally in the marine environment (Heaton 1986; Macko and Ostrom 1994). N:P ratios also provide good diagnostic capability in coastal studies as these can vary between land-based and marine sources of suspended matter depending on the origin of the nutrient supply (Ruttenberg and Goñi 1997a; Ruttenberg and Goñi 1997b).

In this work, we investigated sedimentation rates on 12 reefs along the Adelaide metropolitan coast between Semaphore and Aldinga. Our objective was not only to provide a baseline of dry matter deposition, but also to derive information on the origin of this material. For this purpose, we analysed sediments from reef sites and potential terrestrial sources for nitrogen, phosphorus, nitrogen and organic carbon stable isotopes, and particle size distribution. Samples from terrestrial sources, and selected samples from reefs with the highest sedimentation, were also analysed for their geochemical composition (Al, Ca, Cr, Cu, Fe, K, Mg, Na, Ni, Pb, Sr and Zn).

2 METHODS

Twelve reefs were monitored between Semaphore and Aldinga in August (winter) and November/December (summer) of 2007 (Table 1, Figure 1). Samples were collected using sediment traps moored 1 m above the seafloor for 1 to 3 days. Sampling was generally along the landward boundary of the reefs, but for a few selected reefs both the seaward boundary (Outside) and the landward boundary (Inside) were sampled. Each trap consisted of two PVC tubes with a height to width ratio of 4.7 (height 400 mm, diameter 85 mm), lead weighted on the bottom (40 g) to ensure correct vertical orientation. At each site, sediment traps were deployed at 3 stations 30 m apart, with two replicates per station. Upon retrieval, traps were spiked with $HgCl_2$ to a final concentration of 10 mg L^{-1} to prevent microbial degradation.

Upon return to the laboratory, the contents of sediment traps were sieved (1 mm mesh size) to remove material not part of the passive flux (e.g. mobile organisms such as zooplankton). Sieved samples were vacuum filtered through pre-combusted (350ºC for 3 h) and pre-weighed glass-fibre filters (MFS GF-75, 0.7 μm, 47 mm diameter). Filters were placed in separate pre-combusted glass petri dishes, covered with a glass lid and oven-dried at 50ºC. Before gravimetric analysis, filters were placed in an oven at 50ºC for at least 3 h and then placed in a desiccator with silica gel for 1 h to cool. The filters were then weighed (±0.00001 g). Results were corrected for salt that impregnates the filters. Sediments were gently scraped off the filters with a spatula, homogenized in a mortar and pestle, and combined to provide a unique sample from each station for further chemical analysis.

We also collected 2 replicate samples from the main riverine sources of stormwater to the metropolitan coast (Wilkinson 2005; Wilkinson et al. 2005a), as well as from the quarry rehabilitation site at Maslins Creek, which was used for over 60 years for the extraction of construction sand. For this purpose, the following sites were sampled (Table 1, Figure 1): Torrens River (above the weir at Military Road), Patawalonga River (above the Barcoo Outlet), Field and Christies Creeks (above the high tide water mark), Onkaparinga River (downstream of Main South Road and in the township of Old Noarlunga), and Maslins Creek (open channel eroded gully). Sediments were collected with 67 mm (i.d.) PVC tubes

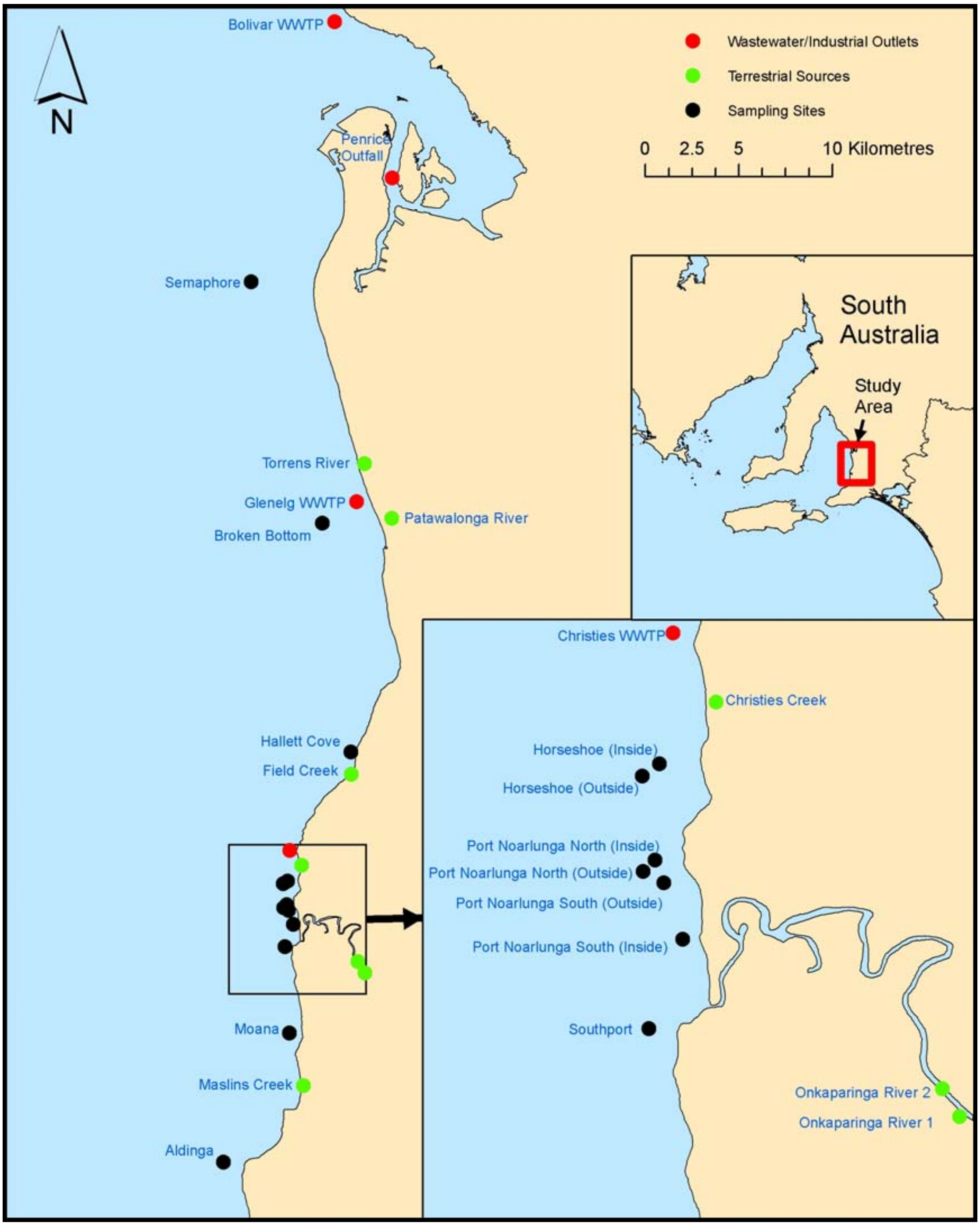

Figure 1. Map of the study area showing the location of sampling sites, potential terrestrial sources and wastewater/industrial outfalls.

Table 1. Coordinates of sampling sites (WGS84) and dates of deployment.

Sampling site	Code	Latitude	Longitude	Date deployed[1] (Winter)	(Summer)
Reefs					
Semaphore	SE	34° 50.826'	138° 26.757'	13-Aug-2007	09-Nov-2007
Broken Botttom	BB	34° 57.801'	138° 28.817'	13-Aug-2007	09-Nov-2007
Hallett Cove	HC	35° 04.422'	138° 29.641'	13-Aug-2007	09-Nov-2007
Horseshoe (Inside)	HI	35° 08.154'	138° 27.811'	13-Aug-2007	09-Nov-2007
Horseshoe (Outside)	HO	35° 08.242'	138° 27.688'	13-Aug-2007	09-Nov-2007
Pt Noarlunga North (Inside)	NNI	35° 08.896'	138° 27.854'	20-Aug-2007	11-Dec-2007
Pt Noarlunga North (Outside)	NNO	35° 08.849'	138° 27.782'	20-Aug-2007	11-Dec-2007
Pt Noarlunga South (Inside)	NSI	35° 09.420'	138° 27.979'	20-Aug-2007	11-Dec-2007
Pt Noarlunga South (Outside)	NSO	35° 09.014'	138° 27.843'	13-Aug-2007	09-Nov-2007
Southport	SP	35° 10.065'	138° 27.736'	20-Aug-2007	11-Dec-2007
Moana	MI	35° 12.551'	138° 27.863'	20-Aug-2007	11-Dec-2007
Aldinga	AL	35° 16.254'	138° 25.971'	20-Aug-2007	11-Dec-2007
Terrestrial sources					
Torrens River	---	34° 56.080'	138° 30.024'	---	28-Nov-2007
Patawalonga River	---	34° 57.660'	138° 30.816'	---	04-Dec-2007
Field Creek	---	35° 05.068'	138° 29.652'	---	28-Nov-2007
Christies Creek	---	35° 07.710'	138° 28.219'	---	28-Nov-2007
Onkaparinga River 2	---	35° 10.494'	138° 29.843'	---	28-Nov-2007
Onkaparinga River 1	---	35° 10.887'	138° 29.918'	---	28-Nov-2007
Maslins Creek	---	35° 14.056'	138° 28.268'	---	28-Nov-2007

[1]For the samples from terrestrial sources, this is the date collected.

capped with rubber bungs. Upon retrieval, the overlying water in the tube was carefully discarded to minimise surface disturbance, the top layer (0-1 cm) sliced, transferred into a pre-combusted glass jar and transported in ice before long-term storage at -20ºC. These samples were oven-dried at 50ºC, homogenized and sieved through a 1 mm mesh to remove large particles, and analysed for particle size distribution, $\delta^{13}C$ signatures, and geochemical composition.

Total nitrogen content, and the stable isotopic signature of nitrogen and carbon ($^{15}N/^{14}N$ and $^{13}C/^{12}C$), were determined using a SerCon EA-CN preparation system coupled to a Hydra 20-20 Continuous-Flow stable Isotope Ratio Mass Spectrometer (CF IRMS). For this purpose, equal amounts from each station were combined into a composite sample for each reef site and sampling period. Two replicates were also analysed for the carbon stable isotopic signature of each terrestrial source. Aliquots for carbon analysis were pre-treated with 1 N hydrochloric acid to remove carbonates, rinsed with MilliQ water to remove hygroscopic salts and oven-dried at 50ºC using a method modified from Hedges & Stern (1984).

Natural isotopic abundances for carbon and nitrogen are reported as $\delta^{13}C$ and $\delta^{15}N$, which correspond to the deviation (in ‰) of the isotopic composition of a sample from an internationally accepted standard (std) (carbon in Pee Dee Belemnite limestone and nitrogen in air) (Peterson and Fry 1987):

$$\delta^{13}C \ or \ \delta^{15}N = \left(\frac{R_{sample}}{R_{std}} - 1 \right) x\, 10^3 \qquad [1]$$

where

$$R = \frac{^{13}C}{^{12}C} \quad or \quad \frac{^{15}N}{^{14}N} \qquad [2]$$

Total phosphorus content was determined for each sample using a Varian Vista Axial Inductively Coupled Plasma-Atomic Emission Spectrometer (ICP-AES) after digestion with nitric and hydrochloric acids (Standards Australia 1997). The samples collected between Horseshoe and Southport reefs in summer contained enough material to allow a larger quantity to be allocated for the digestion step. In addition to phosphorus, these samples, as well as samples from terrestrial sources, were also analysed for Al, Ca, Cr, Cu, Fe, K, Mg, Na, Ni, Pb, Sr and Zn.

Particle size analyses were performed in a Mastersizer 2000 laser diffraction analyser (Malvern Instruments, Worcestershire, UK). For this purpose, we analysed composite reef samples (obtained by combining equal amounts from each station into one sample for each reef site and sampling period), as well as samples from terrestrial sources. Samples were dispersed with a 50 g L^{-1} sodium hexametaphosphate solution in an ultrasound bath for 15 min, then left to soak overnight, and sonicated again for 15 min. Dispersed samples were wet sieved to 1 mm just before analyses to remove possible contamination from filter fibers.

Mineral grain size distributions were analysed with the software package GRADISTAT (Blott and Pye 2001). The Folk and Ward graphical method was used to calculate grain size parameters. This method is relatively insensitive to samples with a large particle range in the tails of the distribution and provides a robust tool to compare compositionally variable samples. Parameters used to describe grain size distributions included the mean grain size, the spread of sizes around the mean (sorting), the symmetry or preferential spread of the distribution to one side of the mean (skewness), and the degree of concentration of the grains relative to the average (kurtosis).

Results were analysed with the software package STATISTICA (StatSoft, Tulsa, OK). Analysis of variance (ANOVA) was used to identify statistical differences (α = 0.05) between site locations and sampling periods (winter vs summer), both of which were treated as fixed factors. To improve normality and heterogeneity of variances, dry matter, nitrogen and phosphorus sedimentation rates were $\log_{10}$-transformed. Hierarchical cluster analysis (single linkage, Euclidean distances) was used as an exploratory technique to extract relationships between variables and sample groupings. The results from ICP-AES analysis were not standardized before cluster analysis to avoid excessive weighting on trace elements. Mineral grain size parameters (mean, sorting, skewness and kurtosis) were also not standardized before cluster analysis; mean grain size is the best indicator of the dominant size class in the distribution and as such was the driving force in defining groupings.

3 RESULTS

Reefs located between Hallett Cove and Southport were subject to the highest rates of dry matter sedimentation along the Adelaide coast, with reefs either north (Semaphore and Broken Bottom) or south (Moana and Aldinga) of this area receiving significantly lower loads of sediments (Figure 2). While not all traps in the southern portion of the study area were deployed at the same time due to logistical constraints (Table 1), the trends observed were the same irrespective of deployment date. Thus we are confident that the pattern observed for each sampling period is a spatial pattern and not a temporal one. Although location along the coast was obviously a major factor in defining sediment loads, these also changed with season (Table 2), particularly at sites between Port Noarlunga and Southport. In this area, dry matter sedimentation rates in summer were on average 2 to 12 times values in winter (Table 3). Sedimentation rates also varied with location of sampling sites in relation to the reef structure, with sites on the seaward boundary generally receiving higher sediment loads than sites on the landward boundary. This difference was particularly evident when sedimentation rates were low in winter (Figure 2).

Table 2. ANOVA results for dry matter sedimentation rates.

Variable	Source	df	MS	F	p
Dry matter (g m^{-2} d^{-1})	Site	11	2.0551	95.11	**<0.001**
	Season	1	1.5040	69.60	**<0.001**
	Site x Season	11	1.0403	48.14	**<0.001**
	Error	111	0.0216		

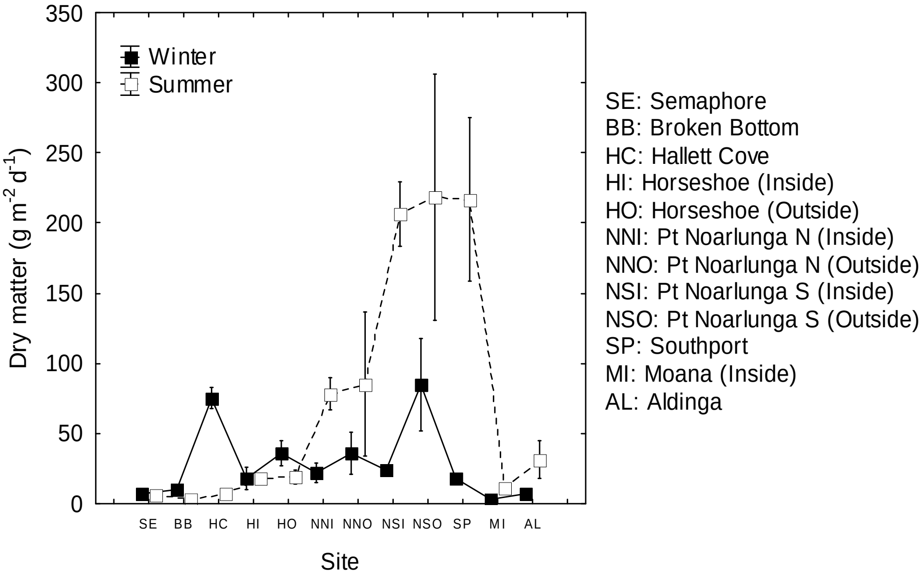

Figure 2. Dry matter sedimentation rates in winter and summer (mean ± SD).

Table 3. Mean dry matter, nitrogen and phosphrous sedimentation rates in winter and summer (mean ± SD).

Site	Dry matter (g m^{-2} d^{-1})		Nitrogen (mmol m^{-2} d^{-1})[a]		Phosphorus (mmol m^{-2} d^{-1})	
	Winter	Summer	Winter	Summer	Winter	Summer
SE	6.56 (0.66)	6.33 (2.49)	2.42	2.25	0.15[b]	0.11 (0.02)
BB	9.82 (0.57)	3.27 (0.38)	3.74	1.18	0.24[b]	0.06 (0.01)
HC	75.25 (7.45)	7.10 (2.82)	27.13	2.05	2.16 (0.19)	0.16 (0.04)
HI	17.92 (8.07)	18.28 (1.60)	4.48	5.93	0.39 (0.22)	0.38 (0.06)
HO	35.94 (8.93)	18.80 (5.29)	10.23	5.50	0.96 (0.31)	0.44 (0.20)
NNI	22.05 (7.12)	78.10 (11.60)	6.35	25.17	0.64 (0.21)	1.81 (0.24)
NNO	35.97 (14.98)	85.21 (51.46)	11.43	21.20	1.05 (0.59)	1.54 (0.99)
NSI	23.90 (2.26)	206.21 (22.71)	6.29	21.70	0.68 (0.08)	2.09 (0.25)
NSO	84.64 (33.21)	218.49 (87.53)	13.15	21.19	1.67 (0.21)	3.69 (1.57)
SP	17.66 (1.61)	216.72 (58.37)	2.76	34.17	0.31 (0.05)	2.66 (0.60)
MI	3.31 (0.73)	10.86 (3.38)	1.52	4.58	0.09[b]	0.22[b]
AL	6.68 (1.31)	31.41 (13.82)	0.74	6.51	0.10[b]	0.45 (0.03)

[a]Only one composite sample analysed per site for each season.
[b]Limited material available, only one composite sample analysed for phosphorus.

The nitrogen and phosphorus contents of sinking sediments indicate that location along the coast will not only play a major role in the amount of sediments reaching particular reefs, but also in their nature (Table 4). Between Hallett Cove and Port Noarlunga North, where sedimentation rates were high, sinking sediments were nitrogen-depleted when compared to sites with lower sedimentation rates further north (Figure 3a). This area, however, had the highest phosphorus content (Figure 3b). In contrast, the extremely high rates of dry matter sedimentation measured between Port Noarlunga South and Southport were driven by the deposition of sediments depleted in both nitrogen and phosphorus. Similarly organic-poor sediments were observed as far south as Aldinga.

The impact of seasonality on the nature of sinking sediments was difficult to ascertain based on nitrogen contents due to the low power of the analysis (i.e. only one composite sample analysed per site for each season) (Table 4). There was, however, a significant decrease in phosphorus content between winter and summer as dry matter sedimentation rates increased. Although the high dry matter sedimentation rates at both Port Noarlunga South and Southport were offset by low nitrogen and phosphorus content, these sites had the highest sedimentation rates for these nutrients along the coast (Table 3).

The different amounts and nature of sinking sediments reaching particular reefs indicates that the source of this material will vary along the coast. The decline in N:P molar ratios and $\delta^{15}N$ signatures from north to south is a clear indication of shifts in origin (Figures 4a,b). This trend was not as clear for $\delta^{13}C$ signatures, which showed little terrestrial influence, particularly for sites north of the Onkaparinga mouth (Figure 4c; Table 5). The clear outlier in this north to south gradient was Moana reef, where sinking sediments had high nitrogen and phosphorus contents, high N:P molar ratios, high $\delta^{15}N$ and low $\delta^{13}C$ signatures, potentially signalling a localized source of organic-rich particles.

Table 4. ANOVA results for the nitrogen and phosphorus content of sinking sediments, and nitrogen and phosphorus sedimentation rates.

Variable	Source	df	MS	F	p
Nitrogen (%)	Site	11	0.036803	8.3171	**<0.001**
	Error	12	0.004425		
	Season	1	0.003750	0.1816	0.67
	Error	22	0.020645		
Nitrogen (mmol m^{-2} d^{-1})	Site	11	0.211870	1.2230	0.37
	Error	12	0.173240		
	Season	1	0.203450	1.0642	0.31
	Error	22	0.191180		
Phosphorus (%)	Site	11	0.000644	7.0320	**<0.001**
	Season	1	0.004467	48.8140	**<0.001**
	Site x Season	11	0.000295	3.2220	**0.003**
	Error	38	0.000092		
Phosphorus (mmol m^{-2} d^{-1})	Site	11	0.108155	17.3142	**<0.001**
	Season	1	0.053479	8.5613	**0.006**
	Site x Season	11	0.078915	12.6332	**<0.001**
	Error	38	0.006247		

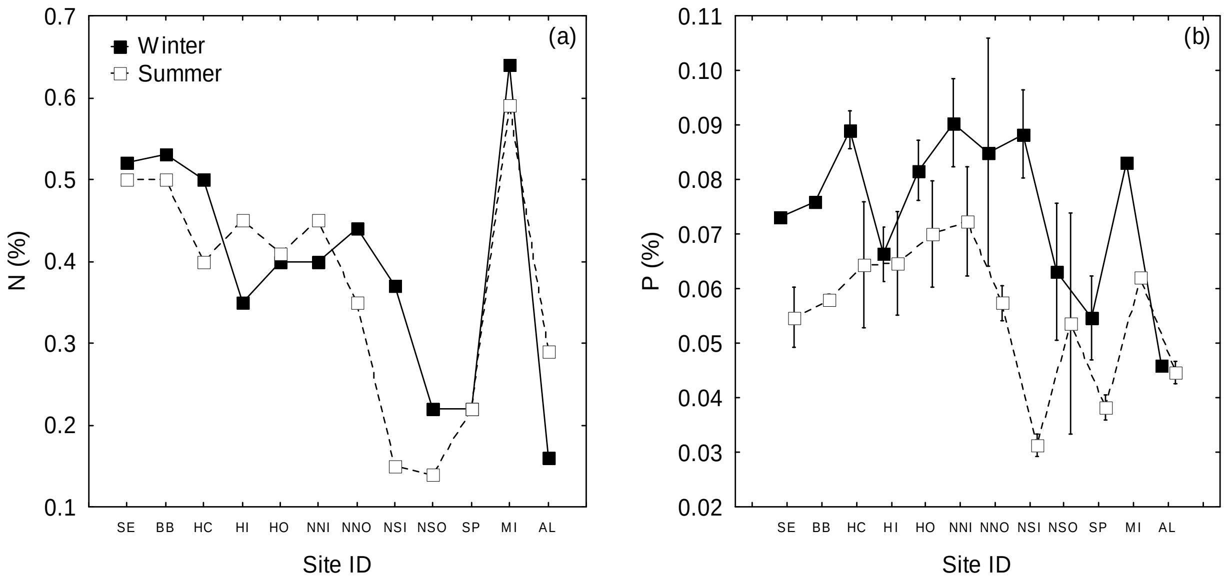

Figure 3. Content of (a) nitrogen and (b) phosphorus of sinking sediments during winter and summer. For nitrogen, only one composite sample was analysed per site for each sampling period. For phosphorus, contents are reported as the mean ± SD.

Table 5. $\delta^{13}C$ signatures of potential terrestrial sources (mean ± SD).

Site	$\delta^{13}C$ (ppm)
Torrens River	-25.7 (0.4)
Patawalonga River	-24.3 (0.6)
Field Creek	-27.7 (0.1)
Christies Creek	-23.2 (0.1)
Onkaparinga River 2	-25.6 (0.1)
Onkaparinga River 1	-24.3 (0.4)
Maslins Creek	---[1]

[1]Concentration below detection limit of approximately 0.2% carbon.

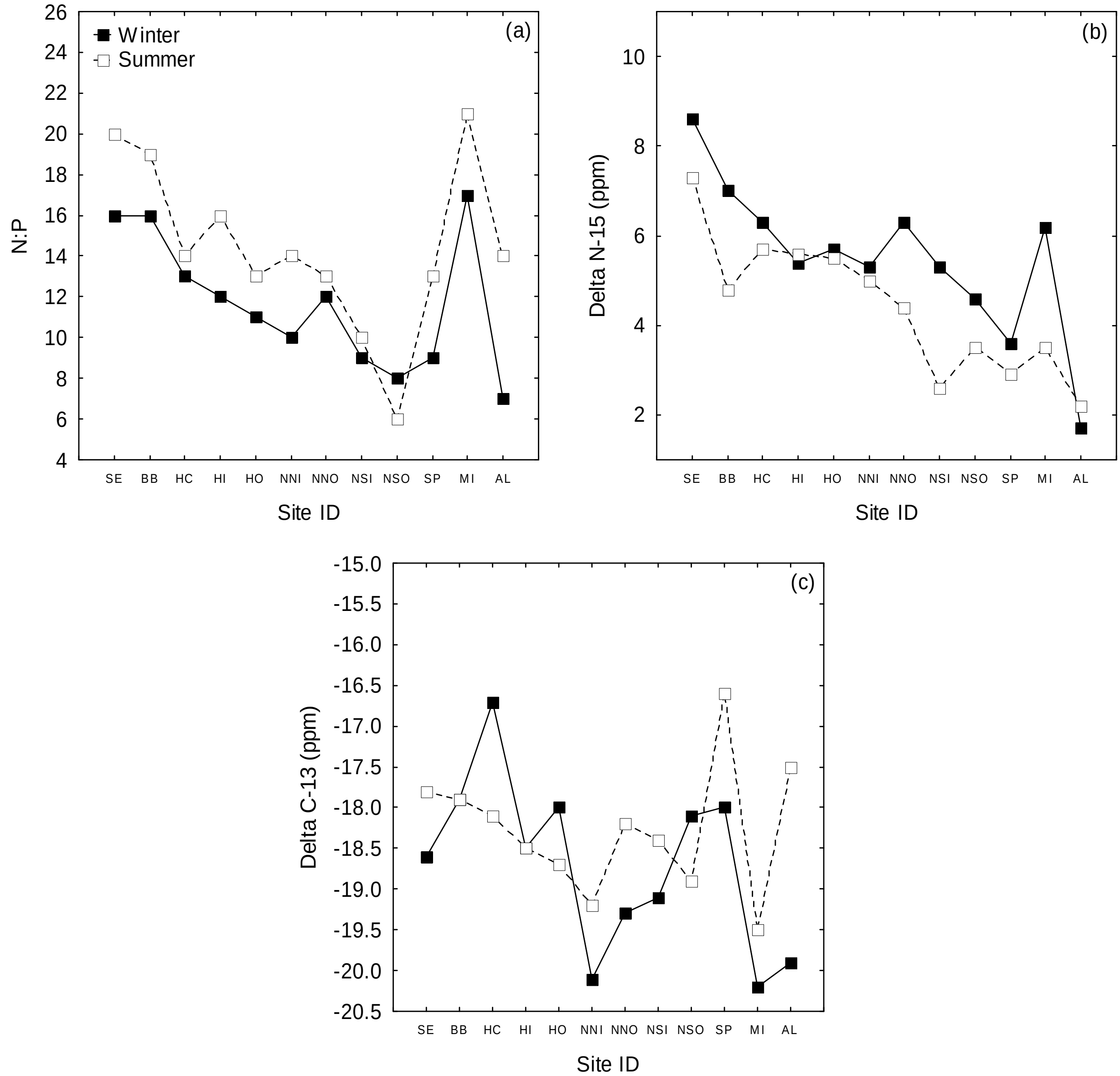

Figure 4. Nitrogen to phosphorus molar ratios (a), $\delta^{15}N$ (b), and $\delta^{13}C$ signatures (c) of sinking sediments during winter and summer.

The detailed elemental scan of a few selected samples from the area of high sedimentation in summer indicates three major groupings (Figure 5a): (1) sediments from Horseshoe reef and the outer reef at Port Noarlunga North were similar to sediments from Field Creek and Christies Creek, while (2) sediments reaching Port Noarlunga South and Southport were similar to samples from the Onkaparinga River, and (3) sediments from Maslins Creek form a separated cluster and were not similar to any of the reef sediments. The inner reef at Port Noarlunga North shows characteristics that are intermediate between groups 1 and 2. We excluded Ca, Mg and Na from this analysis as the reef samples had much higher concentrations of these elements than the terrestrial samples. The differences between the three major groups were driven by concentrations of Al, Fe and K: samples from group 1 north of the Onkaparinga mouth had higher concentrations than samples from group 2 near the mouth of the Onkaparinga River, while samples from Maslins Creek were enriched in Fe, but depleted in Al and K (Figure 5b).

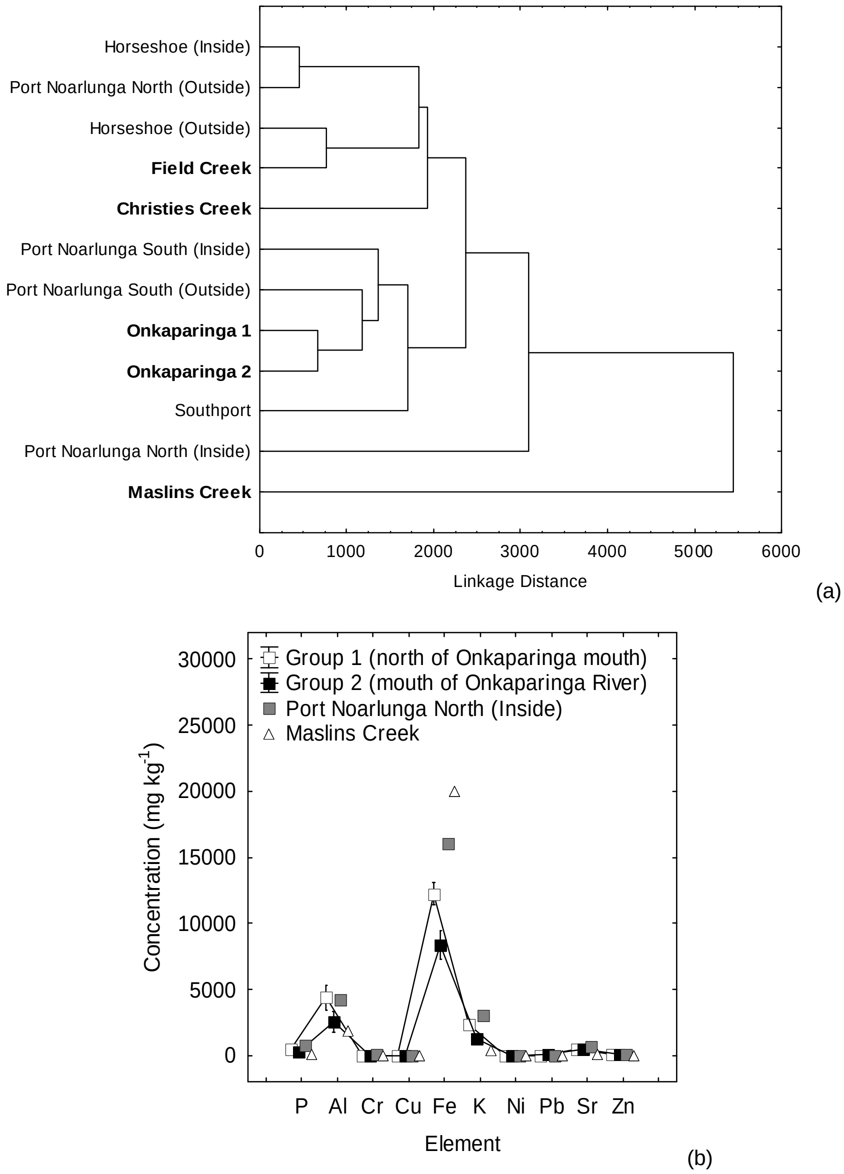

Figure 5. Dendrogram using single linkage (Euclidean distances) highlighting the spatial separation of terrestrial sources (in bold) and sampling sites based on the elemental analysis of samples by ICP-AES (a), and concentrations of several elements measured by ICP-AES (Mean ± SD) for the groupings identified in the cluster analysis (b).

The analysis of particle size distributions showed similar groupings along the coast as the detailed elemental scan discussed above (Figure 6). The particle size distribution of reef sediments had no resemblance to the coarse sands collected from the Barcoo Outlet in the Patawalonga River or from Maslins Creek (Table 6; Figures 7 and 8). Particle size distributions of reef samples collected close to the mouth or south of the Onkaparinga River closely resembled sediments from the Onkaparinga River (Figure 6). In summer, when sedimentation rates were high, this similarity extended as far north as Hallett Cove. In contrast, sediments north of the mouth of the Onkaparinga River were finer and had distributions similar to Field Creek and Christies Creek in the south, and the Torrens River in the north.

Table 6. Particle size characteristics of reef sediments and some potential terrestrial sources.

Site	Mean (μm)	Sorting (μm)	Skewness	Kurtosis
Winter samples				
Semaphore	40	5.10	0.08	1.03
Broken Bottom	45	5.53	0.02	1.06
Hallett Cove	44	4.68	-0.22	0.94
Horseshoe (Inside)	39	4.74	-0.28	0.92
Horseshoe (Outside)	52	4.39	-0.33	0.88
Port Noarlunga North (Inside)	33	4.63	0.00	0.92
Port Noarlunga North (Outside)	48	4.57	-0.09	0.88
Port Noarlunga South (Inside)	83	4.02	-0.40	1.01
Port Noarlunga South (Outside)	33	4.71	0.07	0.99
Southport	70	4.52	-0.25	0.96
Moana	71	4.87	-0.19	0.86
Aldinga	91	4.71	-0.41	0.97
Summer samples				
Semaphore	53	4.20	-0.07	0.98
Broken Bottom	62	4.27	-0.09	0.95
Hallett Cove	81	4.10	-0.17	0.96
Horseshoe (Inside)	61	4.11	-0.11	0.95
Horseshoe (Outside)	67	3.72	-0.19	0.96
Port Noarlunga North (Inside)	45	3.60	-0.09	0.97
Port Noarlunga North (Outside)	47	3.81	-0.13	0.94
Port Noarlunga South (Inside)	83	3.14	-0.36	1.00
Port Noarlunga South (Outside)	81	4.15	-0.27	0.87
Southport	83	3.24	-0.26	1.12
Aldinga	88	3.75	-0.19	0.94
Terrestrial sources				
Torrens River	45	4.02	-0.09	0.86
Patawalonga River	189	3.45	-0.56	2.02
Field Creek	54	6.10	-0.11	0.87
Christies Creek	50	7.76	-0.26	0.76
Onkaparinga River 2	67	4.51	-0.42	1.05
Onkaparinga River 1	75	5.46	-0.27	0.80
Maslins Creek	384	1.33	0.00	0.97

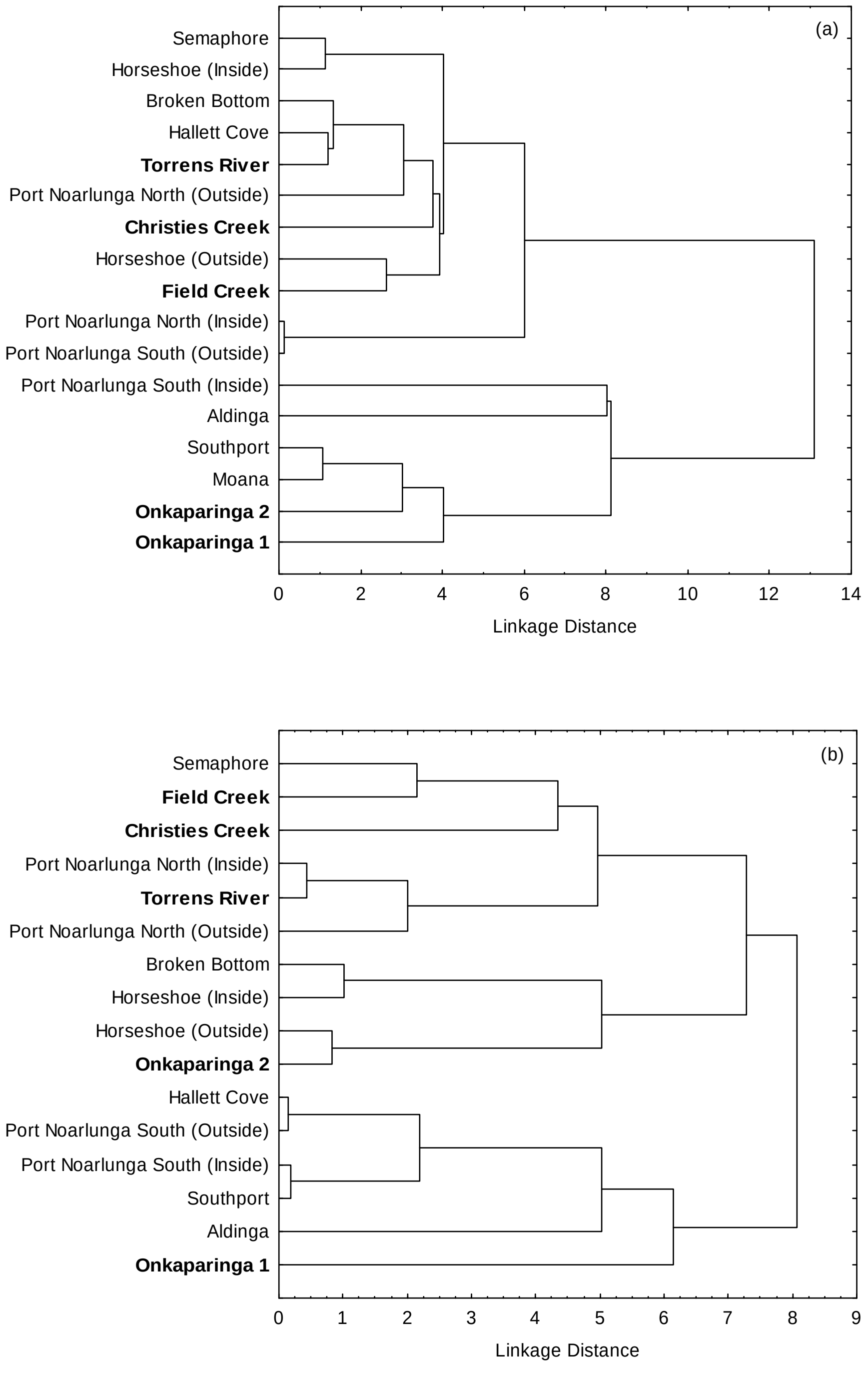

Figure 6. Dendrogram using single linkage (Euclidean distances) highlighting the spatial separation of terrestrial sources (in bold) and sampling sites based on particle size characteristics (mean, sorting, skewness, kurtosis) during winter (a) and summer (b) excluding Maslins Creek and the Patawalonga River as potential terrestrial sources.

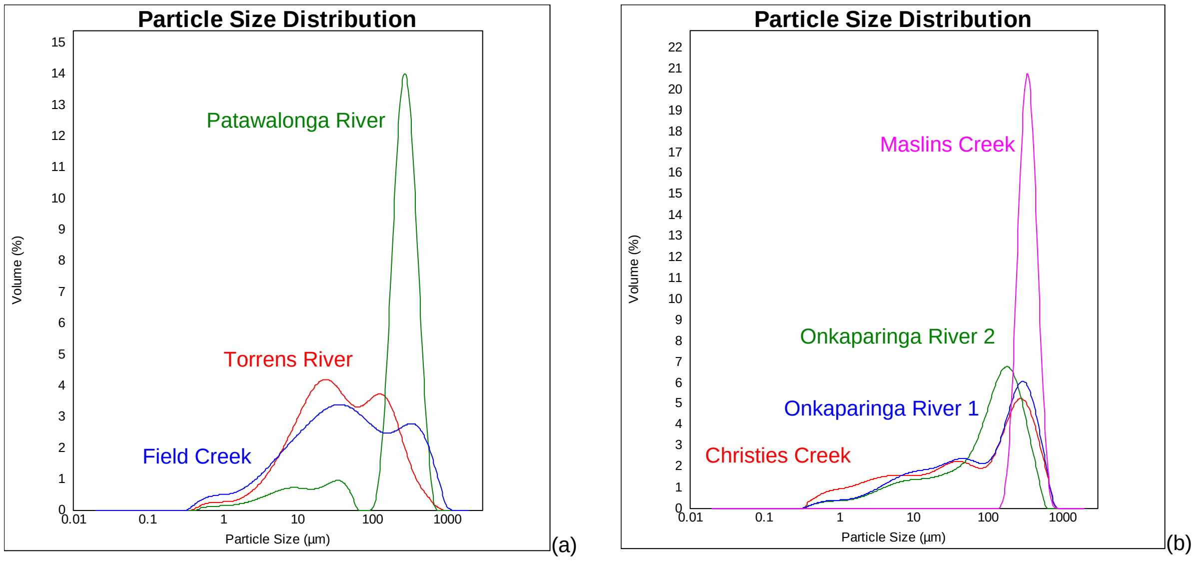

Figure 7. Particle size distributions of potential terrestrial sources from north to south: Torrens River, Patawalonga River and Field Creek (a) and Christies Creek, Onkaparinga River and Maslins Creek (b).

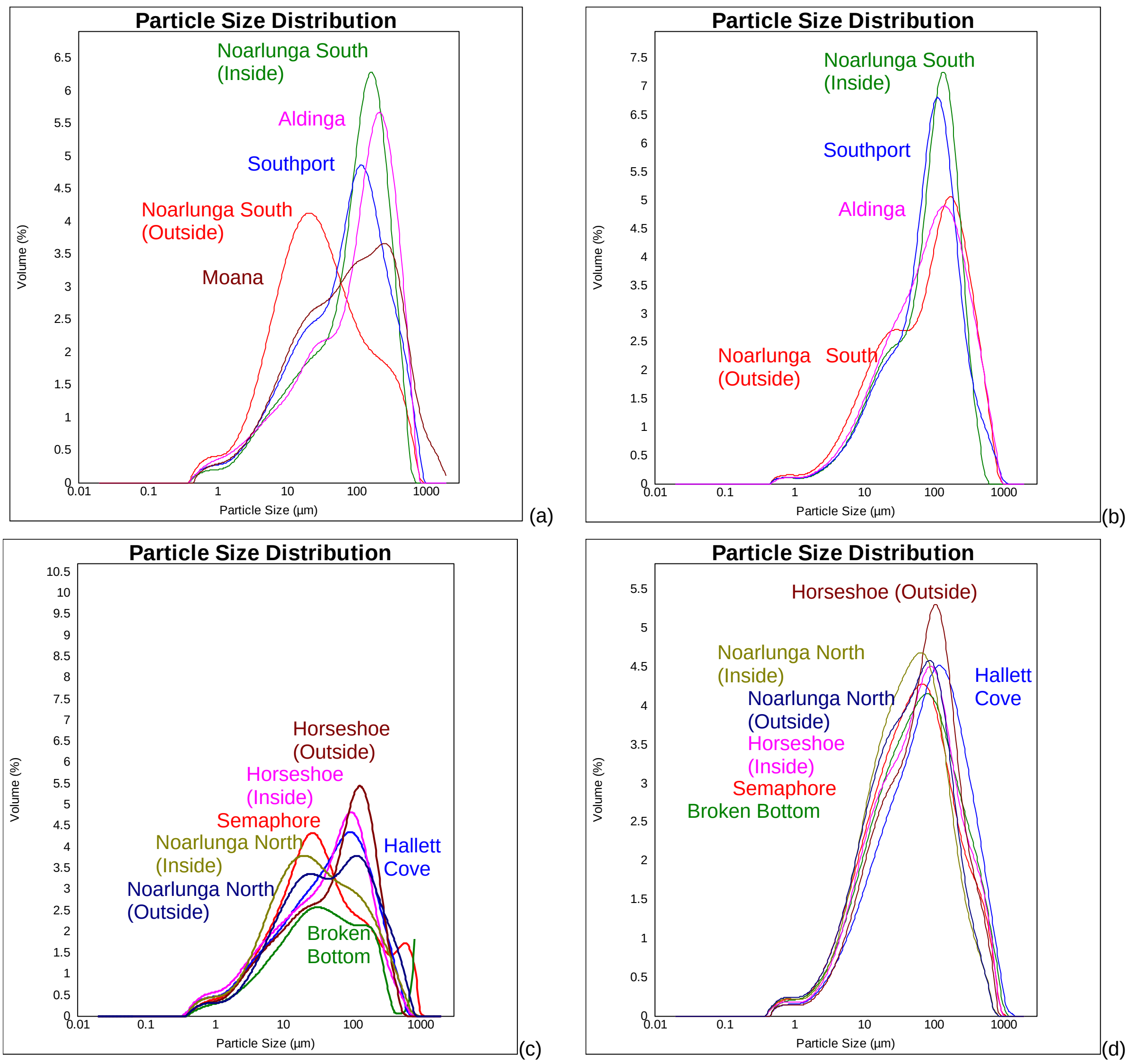

Figure 8. Particle size distributions of sediments reaching reefs near the mouth or south of the Onkaparinga River during winter (a) and summer (b), and north of the Onkaparinga River during winter (c) and summer (d).

4 DISCUSSION

The Onkaparinga River was the major vector of sediments to reefs along the Adelaide metropolitan coast between August and December of 2007. Reefs close or immediately south of its mouth were subject to the highest dry matter, nitrogen and phosphorus sedimentation rates. Sediments reaching these reefs were coarser, and had lower N:P ratios, $\delta^{15}N$ and $\delta^{13}C$ signatures when compared with other sites along the coast, suggesting a riverine origin with negligible wastewater influence. While the Onkaparinga River is estimated to discharge 758 tonnes of suspended matter per year into the marine environment, the load from the only WWTP discharging along this part of the coast at Christies Beach is estimated at a mere 84 tonnes $year^{-1}$ (Wilkinson et al. 2005b). The riverine signature near the mouth of the Onkaparinga River is observed as far south as Aldinga, although dry matter sedimentation rates drastically decrease south of Southport. Sediments collected from the quarry rehabilitation site at Maslins Creek were significantly coarser and had a different elemental composition in comparison to reef sediments, suggesting little influence of this potential terrestrial source over sedimentation in the southern portion of the metropolitan coast.

The area near the mouth of the Onkaparinga River showed particularly high sedimentation rates after a major rainfall event that peaked at 18.4 mm on the 3rd of November (Figure 9). Unfortunately the flow record for the Onkaparinga River at the city of Old Noarlunga, approximately 1.1 km from the river mouth, is only available until the 3rd of November. A comparison of flows from the Field and Christies Creeks and the Onkaparinga River, indicates that the former usually peak one day before the Onkaparinga River. It is therefore plausible that the available data might not cover the peak in the Onkaparinga flow associated with the flood of early November. However, while the catchments for the Christies and Field Creeks are highly urbanised and respond to rainfall all year round, the Onkaparinga River has a predominantly rural catchment, where extreme soil moisture deficit restricts significant runoff to the wetter months of the year, between June and October (Wilkinson 2005; Wilkinson et al. 2005a). If direct inputs from the river were not substantial in early November, stormy conditions might have led to resuspension and transport of sediments deposited during winter, when Onkaparinga flows were high. Alternatively, the erosion of cliff-faces at the mouth of the Onkaparinga River provides another local source of sediments to coastal ecosystems (Bone et al. 2007).

We deployed one set of traps at Port Noarlunga South on the 9th of November, but subsequent traps in this southern area were deployed on the 11th of December. All of these traps measured very high sedimentation rates, irrespective of deployment date. These results suggest that the extreme rainfall event occurring in November led to enough terrestrial sediments in the near-shore zone to sustain high sedimentation rates on the southern reefs up to mid-December. The energetic wave climate in the area, capable of mobilising fine to medium-sized sand for over 90% of the time, together with minimal cross-shore advection and a slow flushing regime (Petrusevics 2005; Pattiaratchi et al. 2007), might have acted to amplify sedimentation rates during this period. Although transport is directed southwards during winter, the onset of the summer sea breeze pattern in November/December, shifting circulation towards the north (Pattiaratchi et al. 2007), was reflected in coarser sediments being advected as far north as Hallett Cove.

North of the Onkaparinga mouth, the Field and Christies Creeks were major vectors of sediments to reefs between Port Noarlunga North and Hallett Cove. The discharge of suspended matter from these creeks into the marine environment is estimated at 146 and 170 tonnes per year, respectively (Wilkinson et al. 2005b). These sediments were finer and enriched in P, Al, Fe and K, when compared to sediments reaching sites near or south of the Onkaparinga mouth. Sedimentation at these and other reefs north of Port Noarlunga did not respond to the major rainfall event occurring in early November, with similar or slightly lower rates in summer in comparison to winter, when river discharges were more prominent (Figure 9).

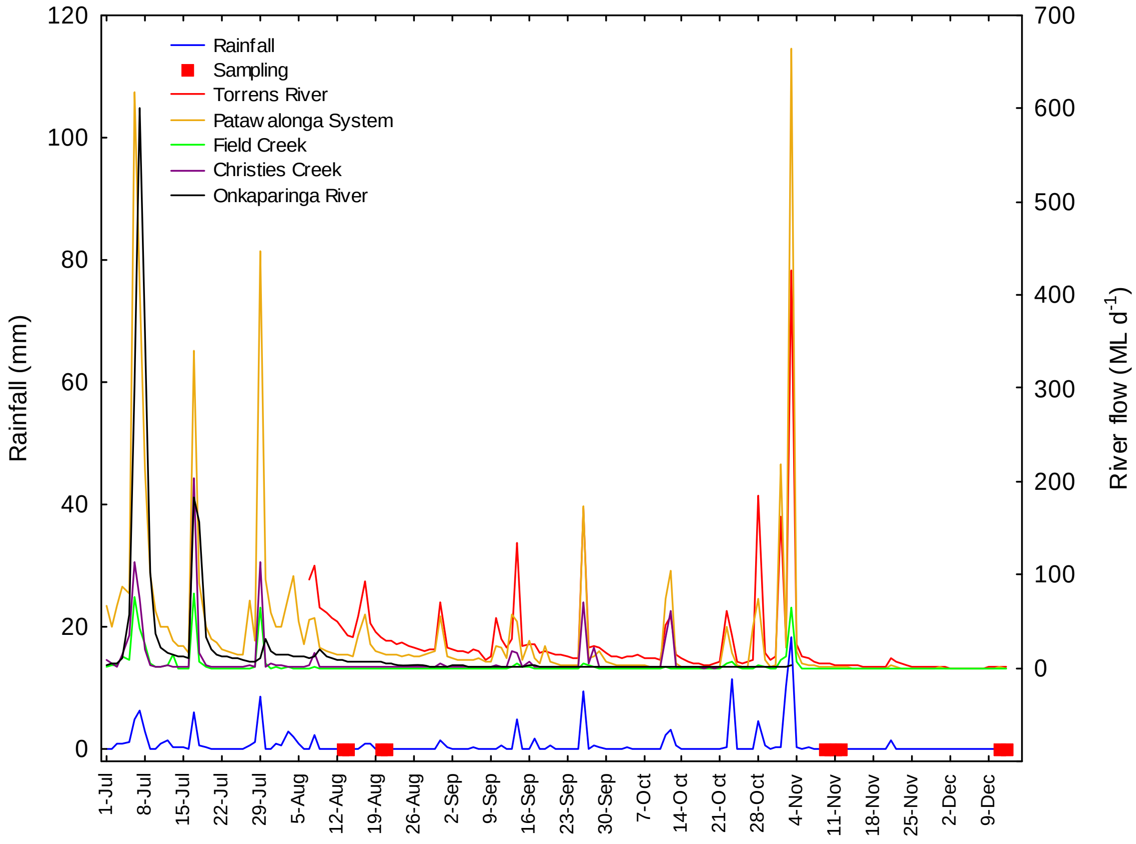

Figure 9. Daily mean river flows (Department for Water, Land and Biodiversity Conservation) and rainfall recorded at the Adelaide Airport (Bureau of Meteorology), with sampling dates highlighted in red. Christies Creek flows after October 21, and Onkaparinga River flows after November 3, are currently unavailable. Torrens River flow is not reported between July and August 7 due to a logger failure. Flows from the Patawalonga were estimated as the sum of flows from the Brownhill Creek and Sturt Rivers.

Further north, the reefs at Semaphore and Broken Bottom had the lowest rates of sedimentation along the coast, but were characterized by the deposition of fine sediments with high $\delta^{15}N$ signatures, high nitrogen content and N:P ratios. These ^{15}N-enriched sediments are likely to derive from 3 potential sources: the WWTPs of Bolivar and Glenelg, with $\delta^{15}N$ signatures between 13 and 18‰, and more importantly, the Penrice soda factory discharging in the Port River/Barker Inlet system with a $\delta^{15}N$ signature of 63‰ (Fernandes, unpublished results)(Figure 1). These sources contribute 487, 471 and 1,000 tonnes of nitrogen per year into the marine environment, respectively (Wilkinson et al. 2005b). Hydrodynamic modelling suggests that the ^{15}N-enriched discharges from the Penrice soda factory have a spatially-large footprint in the coastal strip landward of Semaphore reef, particularly strong during winter as the wind-driven circulation is directed towards the south (Pattiaratchi et al. 2007).

Despite high flows from the Torrens and Patawalonga Rivers (Figure 9), the influence of these sources on sedimentation on the offshore reefs of the northern section of the study area could not be clearly established, except for some similarity in particle size distributions. The high nitrogen isotopic signatures and the high nitrogen contents of sediments suggest a more pronounced wastewater/industrial influence. For comparison, the loads of suspended matter from the Torrens and Patawalonga rivers are estimated at 827 and 999 tonnes year^{-1}, respectively, against values for the Bolivar and Glenelg WWTPs of 1,272 and 223 tonnes year^{-1} (Wilkinson et al. 2005b). Suspended matter loads from the Penrice soda factory are unknown, but total discharges from the Barker Inlet are estimated at 1,279 tonnes year^{-1} (Wilkinson et al. 2005b). In an analysis of SeaWIFS satellite images from the Adelaide metropolitan coast, Petrusevics (2005) also found no significant correlation between discharges from the Torrens river and suspended matter concentrations at sites in the northern part of the study area, suggesting that the transport of land-based discharges to more than 1-2 km off the coast is highly unlikely. The lack of a riverine signature in sediments reaching offshore reefs might also be partially explained by the episodic and transient nature of river loads in comparison to the continuous discharges of wastewater and industrial effluents.

Sediments with high $\delta^{15}N$ signatures, high nitrogen content and high N:P ratios were also observed at Moana reef in the south, suggesting a point source of wastewater contamination. This local influence could originate from groundwater inputs, as the area north of Point Blanche, near Maslins Creek, has been suggested as the only potential source of groundwater to the metropolitan marine environment (Lamontagne et al. 2005).

5 CONCLUSIONS AND RECOMMENDATIONS

This limited dataset indicates that the deposition of terrestrial sediments on reefs located in metropolitan waters decreases with distance from shore, peaking in the near-shore reefs around the mouth of the Onkaparinga River. Reefs between Port Noarlunga and Southport experienced sedimentation rates that were up to 67 times values measured on other reef systems on the eastern side of Gulf St Vincent. These high sedimentation rates were entrained by a major storm event occurring in early November when rainfall reached its highest value since the beginning of July. Rates remained high for over a month after the event. The high sedimentation rates observed in these near-shore reefs are likely a consequence not only of inputs from the Onkaparinga River, but also physical forcings leading to minimal cross-shore advection and strong remobilization of sediments by wave action. Although subject to much lower sedimentation rates, reefs in the northern section of the metropolitan zone were affected by wastewater/industrial effluents and therefore cannot be considered as pristine.

This dataset provides a preliminary baseline of sedimentation along metropolitan reefs, but does not provide enough information to assess deposition on a seasonal or short-term basis. Although the goal was to deploy sediment traps soon after major rainfall events, weather conditions were typically not ideal for deployment for several days or weeks after the events. As a consequence, it is difficult to make a detailed assessment of the impact of floods on coastal sedimentation. Further monitoring campaigns would benefit from a sampling strategy targeted at better capturing short-term temporal patterns. One alternative would be the deployment of sediment traps on fewer sites over a full month and during contrasting runoff conditions (e.g. wettest month of the year vs driest). For this purpose, traps could be permanently moored for the duration of the experiment and collection cups changed every few days. This strategy would help establish the effect of rainfall and river flows on sedimentation.

The present study also had a limited coverage of potential terrestrial sources, with only limited replication achieved for the sources sampled. A more detailed study of the different river catchments and other potential terrestrial sources such as wastewater and industrial effluents, as well as stormwater, would allow the definition of statistically verified composite fingerprints for the different sources. These signatures are necessary for the development of a multivariate mixing model to quantify the importance of each source to sedimentation along the coast under current conditions. This information is crucial if we are to better understand and predict the consequences of management decisions not only on reef structure and functioning, but also on the health of other coastal systems threatened by sedimentation (e.g. seagrass beds).

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