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Importance of marine inputs to the sediment and nutrient load of coastal-plain estuaries: a case study of Pumicestone Passage, south-eastern Queensland, Australia

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Abstract. Sediment and nutrient exchange between Deception Bay and Pumicestone Passage was studied to test the hypothesis that marine input of sediment and associated particulate nutrients may dominate the nutrient loading of coastal-plain estuaries. Estimates suggest that Deception Bay contributes 110–111 × 10^3 t of sediment and 68–74 t of phosphorus annually to Pumicestone Passage. These yearly transports were 10 times the sediment and two times the phosphorus contributed from the catchment. In contrast, Deception Bay contributed only 100–220 t of nitrogen annually to Pumicestone Passage, or 12–25% of the nitrogen contributed by the catchment as a result of leaching from agricultural and horticultural areas and/or from groundwater. However, caution is required when extrapolating these findings to other coastal-plain estuaries since some features may be unique to Pumicestone Passage. In particular, the sediment and phosphorus inputs were dominated by a net northerly flow through the passage and high concentrations of suspended sediment and phosphorus in adjacent coastal waters (Deception Bay).

Introduction

Nutrient enrichment of coastal waters is a major international (Anon. 1990) and national (Zann 1995) problem requiring urgent action. The deterioration of coastal water quality is usually associated with an increased loading of nutrients from point and non-point sources in adjacent catchments and estuaries due to changing land use (Yellowlees 1990; Gabric and Bell 1993). Of the numerous studies quantifying nutrient loading to estuaries from their catchments, most have been in temperate systems where loads are dominated by large disturbed upstream drainage basins and/or sewage effluent discharges (Hager and Schemel 1992; Stanley 1993; Smith *et al.* 1996; Staver *et al.* 1996). Few studies have looked at the nutrient loading of estuaries whose catchments do not have significant nutrient point sources and lie entirely within the coastal plain, and there appear in the literature to be no references to studies of such estuaries in tropical and subtropical regions. These systems have flat catchments, suggesting that fluvial loading of sediment and particulate nutrients may be less important because of lower erosion potential (Yarbro *et al.* 1983). Further, these coastal-plain estuaries are intimately linked with the adjacent coastal waters, suggesting that marine inputs of sediment and associated particulate nutrients may dominate nutrient loading of the system.

Pumicestone Passage in south-eastern Queensland is a subtropical barrier estuary system whose catchment lies entirely within the coastal plain. The passage has a national park and two environmental parks on adjacent land, has been included in the Moreton Bay Marine Park, has diverse biological resources, and is important for commercial fishing and tourism. Increased agriculture and urban sprawl on land surrounding the passage has resulted in increased loading of the system with sediments and nutrients. Most previous studies have concentrated on measuring the sediment and nutrient loading from creeks and rivers that drain into the passage and the ambient nutrient concentrations in the passage (Anon. 1993). There is clearly a close geographical and hydrological relationship between Pumicestone Passage and Deception Bay, but although it has been suggested that 50–67% of the nutrient loading to Pumicestone Passage is coming from Deception Bay (Anon. 1993), there are no field data to support this conclusion. The present study tested the hypothesis that marine inputs of sediment and associated particulate nutrients may dominate nutrient loading of coastal-plain estuaries without significant inputs from point sources; the sediment and nutrient exchange between Pumicestone Passage and Deception Bay was quantified under a range of tidal and river flows, and the sediment and nutrient load entering Pumicestone Passage from Deception Bay was compared with the load entering from the catchment.

Materials and methods

Study area

Pumicestone Passage (63 km^2) is a subtropical barrier estuary consisting of two compartments joined by a constricted channel, and it receives fresh water from eight small creeks: Ningi, Elimbah, Glass Mountain, Tibrogargan, Coonawrin, Coochin, Mellum and Bells (Fig. 1). At its northern entrance, the passage is open to the Pacific Ocean over a shallow unstable bar, and it has a wide unobstructed opening to Deception Bay at

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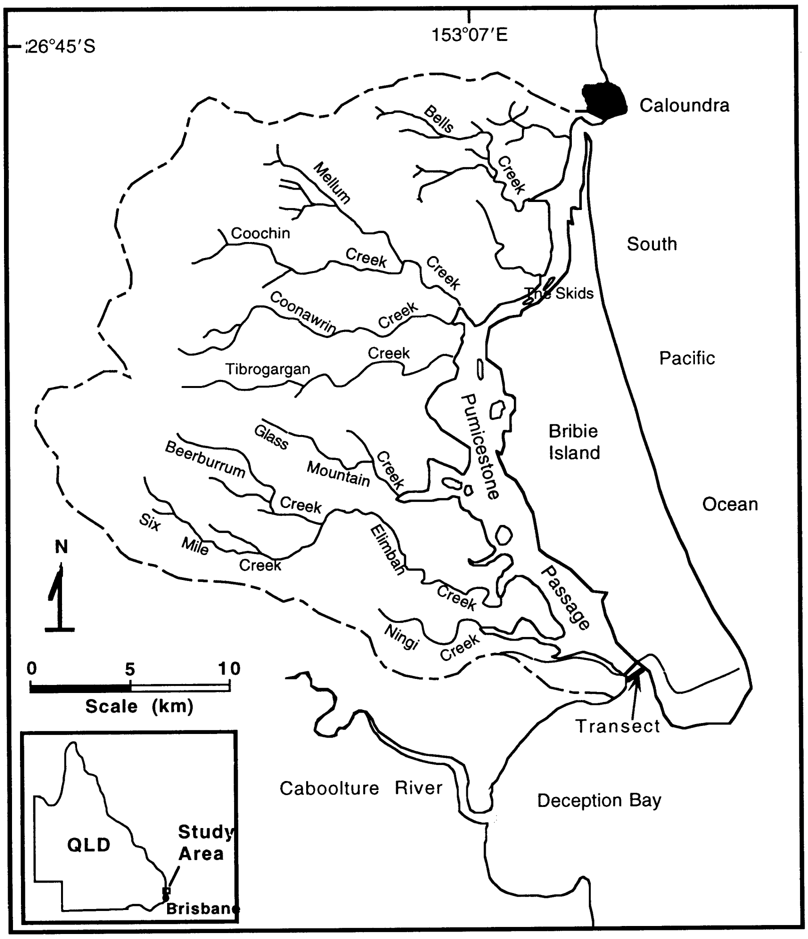


Fig. 1.. Location and extent of Pumicestone Passage and its catchment, and location of the study transect.

the southern entrance. The Skids, a narrow and shallow channel, separates the wider northern and southern entrances. The catchment covers approximately 670 km^2 and supports a variety of land uses, including exotic pine plantations, native and littoral vegetation, horticulture, pastoral and extractive industries, transport corridors, and rural and urban residential dwellings. Increased urbanization in the catchment has exceeded recommendations (Anon. 1993), and the growth predicted for the next 20 years will result in a significant increase in land clearing. The climate in south-eastern Queensland is controlled by two major influences: the subtropical high-pressure belt during winter–spring bringing clear, mainly dry conditions, and easterly monsoonal tradewinds during summer–autumn bringing warm, humid conditions. Tropical cyclones may affect the region between January and April, bringing heavy rainfalls and flooding. Thus, Pumicestone Passage receives episodic, short-lived, large freshwater inputs during summer storms and very few or no freshwater inputs during winter.

Sample collection

A transect was established perpendicular to the longitudinal axis of Pumicestone Passage about 500 m south of the Bribie Island Bridge (Fig. 1). On the basis of an echo-sounding profile of the bottom, the transect was divided into three major lateral bathymetric sections (Kjerfve *et al.* 1981), and a sampling station was established in the middle of each of these sections. Sampling stations were occupied for a 25-h period during neap (31 July to 1 August 1994) and spring (8 to 9 August 1994) tides (dry season) and a storm (17 to 18 February 1995) that coincided with a spring tide. Hourly readings of current velocity and direction (Braystoke current meter) and salinity (Horiba U-10 multiprobe) were recorded at three depths (0.2, 0.4 and 0.8 of the total depth) at each station. A 1-L sample was hand-pumped from each depth at each station and placed in a covered acid-washed bucket, giving an hourly integrated 9-L sample for the cross-section. Unfiltered and filtered (cellulose acetate filter, pore size 0.45 µm) subsamples were collected immediately in 250-mL acid-washed and sample-rinsed polyethylene bottles and kept in the dark on ice until frozen (–20°C) at the laboratory. A 1-L unfiltered sample was also collected for analysis of suspended sediment.

Sample analysis

Water samples were analysed for total phosphorus (TP), total nitrogen (TN), dissolved nitrate (NO_3^-), dissolved ammonium (NH_4^+), and dissolved inorganic phosphorus (DIP) by standard colorimetric methods (Valderrama 1981; Parsons *et al.* 1984). The samples collected during the storm were also analysed for total dissolved nitrogen (TDN) and total dissolved phosphorus (TDP). Total particulate phosphorus (TPP) and total particulate nitrogen (TPN) for all samples were determined by difference. Because the dry-season samples were not analysed for TDN and TDP, dry-season TPP includes dissolved organic phosphorus (DOP) and dry-season TPN includes dissolved organic nitrogen (DON). DOP and DON were determined by difference for the storm samples. Total suspended sediment (TSS) was determined gravimetrically. Details of analytical procedures and associated errors are reported elsewhere (Eyre and Twigg 1997).

Flux calculations

The cross-sectional areas of the three transect sections were calculated at mean sea level from an echo-sounding profile and surveyed widths. Each area was adjusted to account for the change in cross-section as water level varied through the tidal cycle. The average hourly current velocity ($V_{av.}$) for each sample site was calculated from the formula

$$V_{av.} = 0.25[V_{0.2d} + V_{0.8d} + 2(V_{0.4d})],$$

where V_d is the current velocity at the given depth (d). The discharge (m^3 s^{-1}) through each section was calculated by multiplying the adjusted hourly cross-sectional area (m^2) by the average hourly current velocity (m s^{-1}). The three individual section discharges were summed and the total hourly discharge was multiplied by the corresponding hourly sediment or nutrient concentration to give hourly fluxes. A negative flux corresponds to transport out of Pumicestone Passage (ebb), and a positive flux corresponds to transport into Pumicestone Passage (flood); fluxes are given for a 25-h tidal cycle (per tide or per day).

Error calculations

An estimation of the error associated with gross water and nutrient fluxes is critical in evaluating smaller net or residual fluxes, because they contain the sum of all the errors of the measured fluxes (Eyre 1995). Water flux errors were calculated from the sums of the squared component errors (Winter 1981). Water flow measurement involves an error of about ±5% (Winter 1981). The error associated with estimating cross-sectional areas from echo-sounding profiles was estimated to be ±5% (Eyre 1995). Nutrient flux errors were calculated from the formula of Eyre (1995):

$$V_{nf} = u_{wf}^{\,2}V_{nc} + u_{nc}^{\,2}V_{wf} + V_{wf}V_{nc},$$

where V_{nf} is the variance of the nutrient flux, u_{wf} is the mean of the water flux, V_{nc} is the variance of the nutrient concentration, u_{nc} is the mean of the nutrient concentration, and V_{wf} is the variance of the water flux. The errors involved in calculating each of the nutrient fractions are given in Eyre and Twigg (1997). The variance associated with the net or residual flux was determined by summing the individual variances in the gross ebb (negative) and flood (positive) fluxes.

Results and discussion

The three sampling runs were representative of extreme dry and extreme wet conditions. In the two months preceding the dry-season sampling runs, a total of only 44 mm of precipitation had fallen (Fig. 2), which was well below the long-term (55-year) average (Department of Water Resources rainfall data). In contrast, 341 mm of precipitation fell in the six days preceding the storm sampling run, including one day of 100 mm and one of 111 mm. The total precipitation for the month during which the storm sampling run was undertaken was well above the 55-year average for that month (Department of Water Resources).

Although both the neap and spring tide were reasonably symmetrical and maximum spring-tide velocities (0.55 m s^{-1}) were only slightly higher than maximum neap-tide velocities (approximately 0.41 m s^{-1}), the switch between ebb and flood flows occurs more rapidly during spring tides, when there are only brief periods of slack water (Figs 3*a* and 3*b*). As a result, maximum ebb and flood velocities were maintained for longer periods during the spring tide, resulting in a much larger gross transport of water into and out of the passage and a larger net transport of water into the passage during the spring tide than during the neap tide (Table 1). Over a complete neap–spring tidal cycle, there was a net input of 1.61 ± 0.11 × 10^6 m^3 of water per tide, which agrees well with earlier estimates of a mean northerly flow of 1.83 × 10^6 m^3 per tide through the passage based on a one-dimensional hydrodynamic model (Anon. 1982). During the storm (Fig. 3*c*), a large volume of precipitation fell in the catchment and runoff overrode the normal net northerly flow through the passage so that the current velocities were asymmetrical, with much higher maximum ebb velocities (0.95 m s^{-1}) than flood velocities (approximately 0.66 m s^{-1}). There was a corresponding net transport of 5.09 ± 0.36 × 10^6 m^3 of water per tide out of Pumicestone Passage into Deception Bay during the storm (Table 1). Discharge asymmetry in the tidal cycle due to freshwater runoff has been noted in a number of coastal systems (Reed 1987; Ovalle *et al.* 1990; Oliveira and Kjerfve 1993).

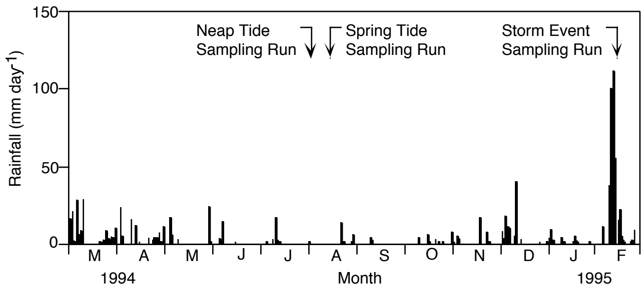


Fig. 2. Daily rainfall (Upper Caboolture Station 540009) for the study area, showing the timing of the three sampling runs.

During the dry season (Figs 3*a* and 3*b*), salinities showed little variation, ranging between about 33 and 34.5 over the tidal cycle. In contrast, salinities ranged between about 18 and 32 over the tidal cycle during the storm (Fig. 3*c*). Under neap-tide conditions, the average salinity of ebb water (33.52) was nearly identical to that of flood water (33.58), suggesting that the water in Pumicestone Passage during the dry season was very similar to that in Deception Bay. However, under spring-tide conditions, there was an average salinity difference of 0.42 between ebb water (33.68) and flood water (34.10), which shows there was still some freshwater input to Pumicestone Passage during the dry season. Since most surface streams in the catchment cease flowing in the dry season, groundwater was probably the major freshwater contributor. Groundwater, which has been polluted by rural and urban development in the catchment

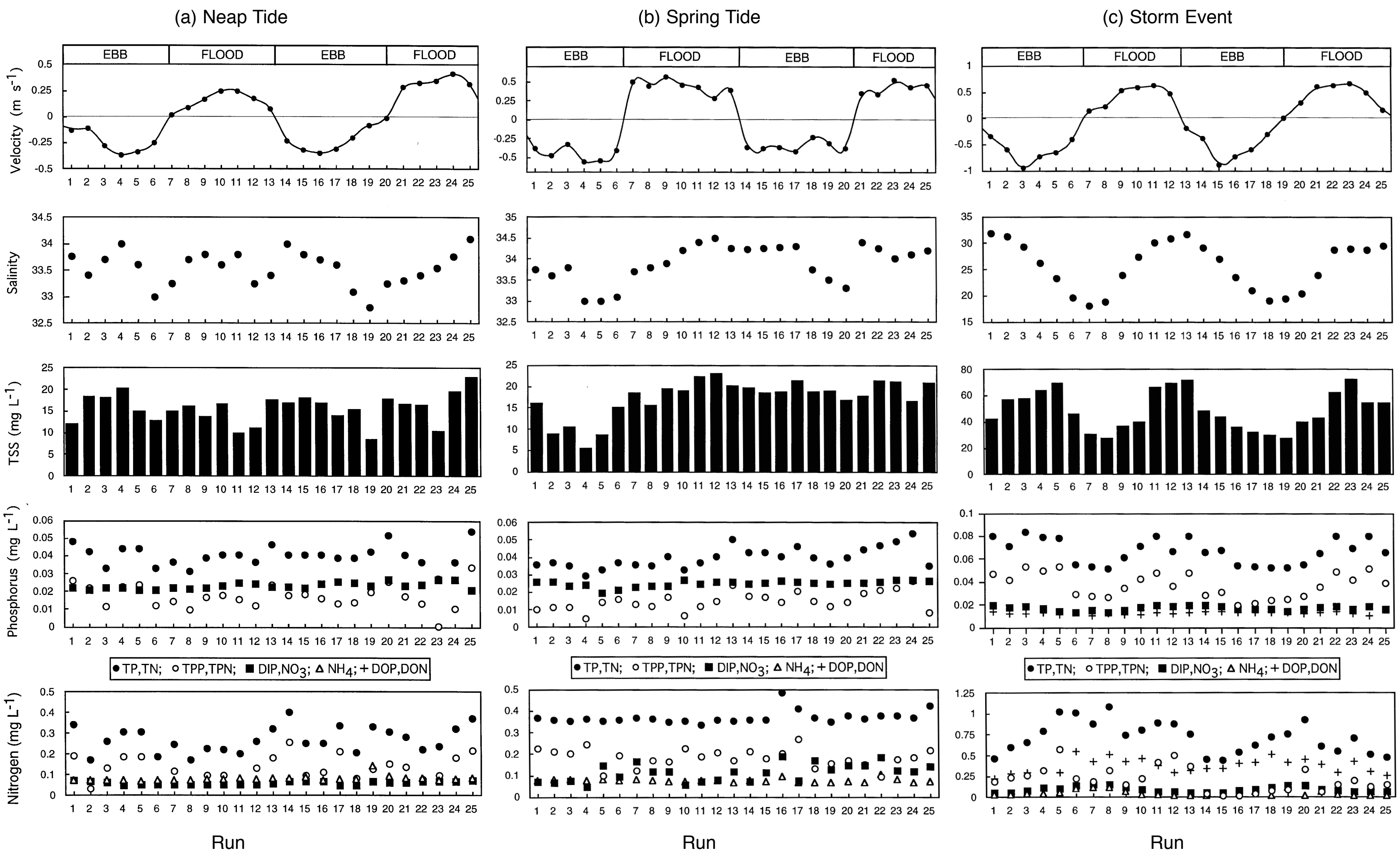
Table 1. Net fluxes per tide between Pumicestone Passage and Deception Bay of water, total suspended sediment, and nutrients

Negative values, transport out of Pumicestone Passage; positive values, transport into Pumicestone Passage. TSS, total suspended sediment; TN, total nitrogen; TPN, total particulate nitrogen; DON, dissolved organic nitrogen; TP, total phosphorus; TPP, total particulate phosphorus; DIP, dissolved inorganic phosphorus; DOP, dissolved organic phosphorus

		Water (m^3, millions)	TSS (kg, thousands)	TN (kg)	TPN (kg)	NH_4^+ (kg)	NO_3^- (kg)	DON (kg)	TP (kg)	TPP (kg)	DIP (kg)	DOP (kg)
Dry	Neap	+1.33 ± 0.09	–28 ± 2	–1364 ± 107	–1958 ± 170[A]	+496 ± 38	+98 ± 8	—	–69 ± 5	–210 ± 15[B]	+141 ± 10	—
	Spring	+1.89 ± 0.13	+629 ± 44	–63 ± 5	–2149 ± 110[A]	–48 ± 4	+2037 ± 167	—	+485 ± 34	+312 ± 22[B]	+172 ± 12	—
	Average	+1.61 ± 0.11	+301 ± 23	–714 ± 56	–2054 ± 140[A]	+273 ± 21	+1068 ± 88	—	+208 ± 20	+51 ± 19[B]	+157 ± 11	—
Wet		–5.09 ± 0.36	+367 ± 26	+7324 ± 577	+5791 ± 502	–747 ± 57	–32 ± 3	+2312 ± 219	–178 ± 12	+319 ± 23	–52 ± 4	–446 ± 32

[A]Includes DON. [B]Includes DOP.

Fig. 3. Vertically and cross-sectionally averaged current velocities, salinities, and concentrations of total suspended sediment (TSS), phosphorus and nitrogen at the southern entrance to Pumicestone Passage over *(a)* a 25-h neap tide during the dry season, *(b)* a 25-h spring tide during the dry season, and *(c)* a 25-h spring tide during a storm.



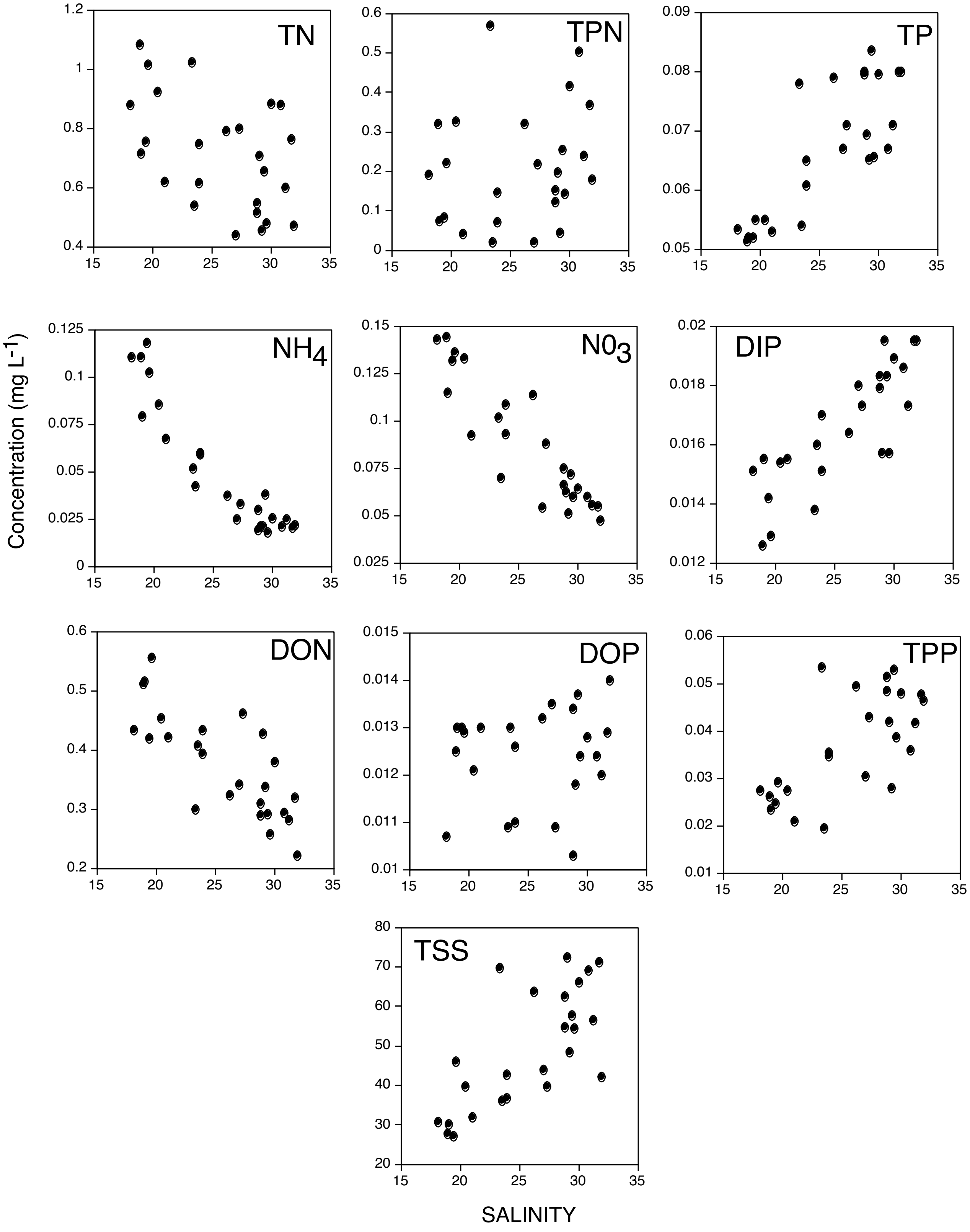


Fig. 4. Concentrations of total suspended sediments (TSS), nitrogen and phosphorus during the storm sampling run plotted as a function of salinity. Higher concentrations at the high-salinity end suggest Deception Bay as the source and higher concentrations at the freshwater end suggest the Pumicestone catchment as the source.

(Anon. 1992), may be an important source of nutrients to Pumicestone Passage during the dry season. The outflow of fresh water during the storm was illustrated by the average salinity difference of 2.04 between ebb water (24.69) and flood water (26.73). The low salinity of the flood water, compared with that from the dry season, shows that Deception Bay was also appreciably influenced by freshwater inputs. Probable sources of fresh water include the Caboolture, Pine and Brisbane Rivers, direct rainfall on the bay, and fresh water discharged from Pumicestone Passage during the previous ebb tide.

Neap-tide and spring-tide TSS concentrations (Figs 3*a* and 3*b*) were similar, mostly falling between about 10 mg L^{-1} and 20 mg L^{-1}. In contrast, storm TSS concentrations (Fig. 3c) were much higher and more variable, with a range of 27 mg L^{-1} to 72 mg L^{-1}. Linear regression of TSS as a function of salinity shows that 52% and 64% of the TSS variability during the storm and spring tide, respectively, may be explained by the variation in salinity. The very poor relationship (r^2 = 0.23) between TSS and salinity during the neap tide was probably a result of the very small variation in salinity. TSS concentrations show a very poor relationship with current velocity for the neap (r^2 = 0.06) and spring (r^2 = 0.06) tides and the storm (r^2 = 0.14), suggesting that the TSS variability not explained by salinity variation was related to wind events. The role of wind in estuarine transport of suspended sediment has been well documented in other studies (e.g. Weir and McManus 1987; Leonard *et al.* 1995; Wolanski *et al.* 1995).

Because higher TSS concentrations were associated with higher salinities, average TSS concentrations in flood waters were higher than those in ebb waters for the dry season, which, when combined with a net input of water, results in a net dry-season input of TSS to Pumicestone Passage (Table 1). Although there was a small net loss of TSS (28 000 kg) during the neap tide, the large TSS input (629 000 kg) during the spring tide suggests that during a complete neap–spring tidal cycle there was a net TSS input of 301 000 kg per tide to Pumicestone Passage (Table 1). Imported sediment is probably trapped in the passage when water currents are slowed by submerged vegetation (e.g. mangroves, salt-marsh and seagrasses). The longer the submergence the greater the trapping, which, combined with the larger net input of water, may explain why more sediment was imported during spring tides. During the storm, there was a net outflow of water from the passage but still a net input (367 000 kg per tide) of TSS because of very high TSS concentrations in Deception Bay (flood water) compared with those in Pumicestone Passage (ebb water) (Fig. 4). This result is similar to that for the Peel Inlet in Western Australia, where there was a net input of water to the estuary during winter but a net output of nutrients due to high nutrient concentrations in the estuary (Black *et al.* 1981). Sediment may have been resuspended from the bottom of Deception Bay, which is generally shallow (3 to 5 m), or from the large mud banks at the southern end of Pumicestone Passage; in either case, sediment would have been mobilized by wind and waves associated with the storm. Alternatively, a sediment-laden Caboolture River plume may have extended into Pumicestone Passage (Fig. 1). During a recent flood, the Caboolture River plume was observed extending into Deception Bay beyond the southern entrance to Pumicestone Passage (Eyre and Davies 1996).

Concentrations of dissolved phosphorus (P) and nitrogen (N) (Figs 3*a* and 3*b*) for the neap and spring tides show little variation through the tidal cycle, reflecting the small variation in salinity. Concentrations of particulate P and N show a much larger variation than the dissolved fractions, reflecting the variability in TSS concentrations. Pumicestone Passage imported inorganic N and exported organic N during the dry season, with an overall small net export of 714 ± 56 kg of N per tide (Table 1) to Deception Bay. The net loss of TPP (210 ± 15 kg) during the neap tide was most likely associated with the corresponding net loss of TSS. A larger net input of TPP during the spring tide (312 ± 22 kg per tide) suggests that during a complete neap–spring tidal cycle there would probably be a net TPP input to Pumicestone Passage (i.e. 51 ± 19 kg per tide; Table 1). DIP was imported during both neap-tide and spring-tide conditions. Overall, Pumicestone Passage imported both inorganic and organic P from Deception Bay during the dry season, with a net import of 208 ± 20 kg of P per tide (Table 1).

The ‘outwelling hypothesis’ (Odum 1980) suggests that temperate salt-marsh systems typically import particulate nutrients and export dissolved nutrients (e.g. Jordan *et al.* 1983; Dankers *et al.* 1984). In contrast, tropical mangrove systems appear to be very finely balanced, with little net annual exchange of dissolved nutrients (e.g. Boto and Wellington 1988; Ovalle *et al*. 1990; Alongi 1996), but they may export some particulate N (Alongi *et al.* 1992). Under normal conditions (i.e. not during storms), Pumicestone Passage does not appear to fit either of these models, because it imports dissolved nutrients and exports TPN. However, the extent to which tropical mangrove and temperate salt-marsh systems either import or export nutrients depends on a range of factors such as geomorphology, climate, hydrology, the type of mangrove (i.e. riverine, fringe, basin forest) being studied, and the maturity of the system (Valiela 1983; Dame and Gardner 1993; Rivera-Monroy *et al.* 1995; Alongi 1996). In contrast to many salt-marsh and mangrove nutrient-exchange studies, which focus on individual components of the system, the material exchanges measured in the present study integrate processes in the catchment, intertidal areas, tidal creeks and open water, hence differences in the exchange of material would be expected. The import of dissolved nutrients and export of particulate nutrients has also been found in other tropical systems (Guerrero *et al.* 1988; Rivera-Monroy *et al.* 1995).

Further, although Pumicestone Passage imports dissolved nutrients, concentrations did not differ significantly (Mann–Whitney $\alpha = 0.05$) between dry-season flood and ebb tides; this demonstrates the role of the net northerly flow of water through Pumicestone Passage in controlling fluxes of dissolved nutrients under normal conditions. However, this net unidirectional flow may not be characteristic of all barrier-island estuaries; Hinchinbrook Channel, a similar barrier-island estuary in north-eastern Queensland, has negligible net residual currents (Wolanski *et al.* 1990). This suggests that the pattern of sediment and nutrient exchange found in Pumicestone Passage may not necessarily be characteristic of all barrier-island estuaries.

During the storm, both P and N concentrations were much more variable (Fig. 3*c*), with Pumicestone Passage acting as a source of dissolved N (NH_4^+, NO_3^-, DON), as illustrated by the increasing concentrations with decreasing salinity (Fig. 4), and Deception Bay acting as a source of P (DIP, DOP, TPP), as illustrated by the increasing concentrations with increasing salinity (Fig. 4). In contrast to the case for the dry season, when nutrient fluxes were dominantly controlled by residual water fluxes (i.e. net northerly flow), these concentration differences in the wet season appreciably influence net nutrient fluxes. During the storm, there was a small export of dissolved inorganic N and a large input of organic N, resulting in a large net input of 7324 ± 577 kg of N per tide to Pumicestone Passage from Deception Bay (Table 1). Although Deception Bay appears to be a source of DIP, DOP and TPP during the storm, only TPP was imported into Pumicestone Passage (319 ± 23 kg per tide), corresponding to the large net increase in imported TSS. The dissolved N exported out of Pumicestone Passage was probably leached from agricultural and horticultural areas in the catchment and flushed out of mangrove and salt-marsh areas. The increase in DIP and DOP concentrations in Deception Bay was most likely due to release from the bottom sediments and pore waters when sediment was resuspended during the storm (Holdren and Armstrong 1980; Boström *et al.* 1988; Vidal 1994).

Yearly fluxes and management implications

A knowledge of the sediment and nutrient loads coming from Deception Bay and the Pumicestone Passage catchment will allow resources to be directed to problem areas. However, calculation of yearly fluxes on the basis of the three sampled tides is difficult; the flux of sediments and nutrients for dry-season conditions can be estimated with reasonable certainty, but the loads transported during storms are much more difficult to quantify. With only one tide sampled during a single storm, it is not known how long the effects of storms last (i.e. how long it is before sediment and nutrient fluxes return to normal). To assess the sensitivity of annual sediment and nutrient fluxes between Pumicestone Passage and Deception Bay to the length of possible storms, the daily storm fluxes were applied to a period of 5–20 days (i.e. the length of time over which a single storm may influence fluxes) and a range of annual fluxes were calculated.

Yarbro *et al.* (1983) suggest that estuaries with flat coastal-plain catchments, such as Pumicestone Passage, are likely to have a dominance of marine over fluvial input of sediment because of the low erosion potential. Comparison of the present estimates of yearly sediment flux from Deception Bay with estimates (Anon. 1993) of the yearly flux from the catchment show this to be the case in Pumicestone Passage, with Deception Bay dominating inputs of sediment (up to 91%) and P (up to 67%) (Table 2). The time over which storms may influence sediment and nutrient fluxes has little effect on the yearly transports of suspended sediment and P (Table 2), suggesting that the estimated fluxes are reasonably accurate. Yearly P transport appears to be dominated by sediment-bound transport, as has been reported in other Australian studies (Cosser 1989; Eyre 1995; McKee and Eyre 1996). These findings have important implications for management, because reduction in sediment and P loss from the catchment, through better management practices, will not necessarily lead to any recognizable improvements in water quality in Pumicestone Passage. Management resources might be better directed towards identifying and controlling the sediment and P sources within Deception Bay. However, these findings may not be generally applicable to all coastal-plain estuaries. For example, marine inputs of sediment and P may not dominate in systems that do not have a net unidirectional flow and/or high concentrations of suspended sediment and phosphorus in adjacent coastal waters. This study has simply emphasized the possibility of marine dominance of sediment and P budgets of coastal-plain estuaries.

In contrast to the yearly sediment and P fluxes, which are dominated by inputs from Deception Bay, yearly N fluxes to Pumicestone Passage are dominated by catchment inputs. The estimate for yearly N fluxes appears less certain than the

Table 2. Yearly sediment and nutrient fluxes to Pumicestone Passage from Deception Bay and the catchment

	Yearly flux from Deception Bay	Yearly flux from the catchment[A]
Total suspended sediment (t, thousands)	110.2 ± 8.4 to 111.2 ± 8.4	10.5
Total phosphorus (t)	68.2 ± 7.1 to 74.0 ± 7.3	36.8
Total nitrogen (t)	99.9 ± 30.9 to 220.4 ± 23.0	865.4

[A]Anon. (1993).

yearly sediment and P fluxes because of the influence of storms (Table 2). However, the large difference between the inputs from Deception Bay and the catchment suggests that the influence of storms is unlikely to change the overall conclusion that the catchment is the major contributor of N to Pumicestone Passage, with export from agricultural and horticultural areas and groundwater leaching as the most likely sources. Any management practices that reduce N losses from the catchment are likely to improve water quality in Pumicestone Passage.

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