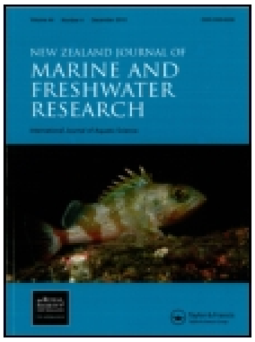

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Robert G. Bell

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Behaviour of dissolved silica, and estuarine/coastal mixing and exchange processes at Tairua Harbour, New Zealand

ROBERT G. BELL
NIWA-Ecosystems
National Institute of Water & Atmospheric Research Ltd
P. O. Box 11–115
Hamilton, New Zealand

Abstract The spatial and temporal variability of dissolved reactive silica (DSi) and salinity in Tairua Harbour (Coromandel, New Zealand) were investigated along with that of the riverine inputs and adjacent coastal waters. In all surveys, covering a range of fresh water discharges and seasons, the very high linear correlations between DSi concentration and salinity indicated conservative behaviour, with physical dilution being the only process having any effect on the distribution of DSi in both estuarine and coastal waters. The tidal exchange of DSi, and hence estuarine water, with the coastal water body was high, with around 82% of the incoming flood tide comprising "new" ocean water. This exchange process was strongly influenced by the quasi-periodic non-tidal alongshore current, but only weakly by variation in river discharge and tidal range. It appears that complete mixing of fresh water (under normal flow conditions) and riverine solutes occurs over a relatively narrow coastal zone (2–3 km) along this stretch of the Coromandel Peninsula.

Keywords silica; tidal exchange; mixing processes; tracers; estuary; coastal waters; rivers; Tairua; New Zealand

INTRODUCTION

Estuarine mixing and subsequent exchange with adjacent coastal waters are fundamental physical processes governing biological, chemical, and sediment interactions within coastal and estuarine systems, which have seldom been linked in previous New Zealand studies.

During estuarine and coastal mixing phases, if a linear relationship exists between the concentration of a particular dissolved constituent and a conservative indicator of mixing between sea water and fresh water (e.g., salinity), then the behaviour of the constituent can be described as conservative (Liss 1976). Conversely, any deviation from conservative behaviour will result in curvilinear (non-linear) relationships with salinity, which are indicative of either addition or removal processes, depending on the sense of curvature. However temporal changes in the end-member (river and ocean) concentrations, which anchor extreme ends of a mixing curve, can easily result in misinterpretation of these curves, particularly in estuarine systems with flushing times greater than a few days (Loder & Reichard 1981). Similar problems can arise with multiple source inputs within an estuary or coastal area (Boyle et al. 1974; Liss 1976).

Conservative behaviour is basic to determining the suitability of various naturally occurring constituents which could be used as tracers to quantify the degree of mixing of inputs to an estuary and the subsequent exchange with adjacent coastal waters. Measurement of several conservative or "quasi-conservative" tracers can therefore be used to identify water types from multiple sources which make up the mixture of a given parcel of coastal or estuarine water, provided the difference in tracer concentrations for each source is large enough to discriminate between sources (Helder et al. 1983). Using this approach one is able to deduce water movements, exchange rates, or relative contributions of various catchments or estuary outflows on a much larger scale than is possible using artificial tracers such as dyes (Hunt & Foster 1977; Mackas et al. 1987). In addition to the commonly used natural tracers of salt (salinity) and heat (temperature) content, dissolved silica and fluorescence have been successfully used in

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estuaries and coastal waters (e.g., Hunt & Foster 1977; Helder et al. 1983).

The dominant dissolved form of silicon in most natural waters (pH < 9) is undissociated monomeric silicic acid (H_4SiO_4) (Aston 1983), which is commonly referred to as dissolved reactive silica (DSi). Owing to weathering of silicate minerals, riverine concentrations can be up to two orders of magnitude greater than average concentrations found in oceanic surface waters (Liss 1976). This enhances the potential value of DSi as a means to separate relative fresh water and sea water contributions. Low concentrations of DSi occur in sea water near the surface (commonly < 500 µg Si l^{-1}) due to the extensive biological uptake of silica by marine organisms (primarily diatoms) which incorporate DSi in their frustules. However DSi undergoes a regeneration cycle in the open ocean, when this skeletal material dissolves as it settles down through the water column (DeMaster 1981), and therefore can exhibit non-conservative behaviour.

A large number of studies world-wide have lead to varying conclusions on the in-situ behaviour of DSi in different estuaries, as summarised by DeMaster (1981) and Blanchard (1988). Behaviour was usually either conservative or subject to in-situ uptake or removal, ranging up to 100% removal but averaging c. 20%. The conclusion from these studies is that the behaviour of silica is often conservative, but this should not be assumed, until proven by in-situ measurements over various weekly to seasonal time scales or at least comparison with estuaries with similar hydraulic characteristics and inputs. A few studies in New Zealand have investigated the distribution of DSi in some of our estuarine and coastal waters (Slinn 1968; Grundy 1985; Taylor & Taylor 1985; Hunter & Tyler 1987) and oceanic waters (Bradford 1983; Hawke 1989), usually as an integral part of a study on nutrient and phytoplankton interactions.

This paper considers both estuarine mixing and exchange with adjacent coastal waters at Tairua Harbour (Fig. 1), which has characteristics typical of many of the barrier-enclosed estuaries of the north-east coast of the North Island of New Zealand (Hume & Herdendorf 1988, 1992). Mixing and exchange processes were elucidated by investigating spatial changes in DSi concentration and salinity, both in the estuary and adjacent coastal waters and temporal variability over a tidal cycle at the tidal entrance, under various seasonal, tide range and river flow conditions. The prospect for using silica as an additional natural tracer for estuarine mixing and tidal exchange studies in similar coastal and estuarine systems was also examined.

SAMPLING AND METHODS

Study area and catchment geology

Tairua Harbour is an elongate 13.5 km long barrier-enclosed estuary (Hume & Herdendorf 1988) on the eastern Coromandel Peninsula, North Island, New Zealand (Fig. 1). It is sheltered from the sea by the 2.7 km Pauanui sand spit to the south and the 1.2 km long Ocean Beach tombolo which joins Paku Mountain to the mainland (Fig. 1). The area serves mainly as a summer beach resort with no significant effluent discharges to the estuary. The estuary is mesotidal (spring tide range = 1.6 m), with an entrance channel c. 180 m wide and reaching a maximum depth of 6.5 m below mean high water spring (MHWS) tide level. The mean depth of the estuary is just under 2 m and the extensive intertidal zone comprises c. 70% of the area at MHWS. Tairua Harbour has a short flushing time of 1.3 tidal cycles to turn over the tidal prism, and takes 2.3 days for the replacement of the mean annual fresh water discharge to the estuary.

The 280 km^2 forested catchment of the Tairua estuary (inset, Fig. 1) rises to 830 m elevation in the steep and rugged Coromandel Range. The main freshwater inputs draining the upper catchment are the Tairua River and the Hikuai River tributary (Fig. 1). Tairua River is gauged at Broken Hills (8 km further upstream from the cut-off in Fig. 1), which drains the large southern hinterland of 112 km^2 yielding a mean annual discharge of 8 $m^3 s^{-1}$, whereas the Hikuai tributary drains the north-west comprising 8.5% of the total catchment area. The catchment lithologies are predominantly weathered andesite, dacite, and rhyolite (Schofield 1967), capped by late Quaternary tephras. The weathered rock and tephra are extremely susceptible to erosion and landslip once the vegetation cover is removed (Hume & Gibb 1987), which provides a ready source of silica to the rivers.

Sampling methods

Five estuarine and two coastal surveys were conducted during 1983–90 in the Tairua area, generally in winter or spring. The conditions and basic approach for each survey are summarised in Table 1.

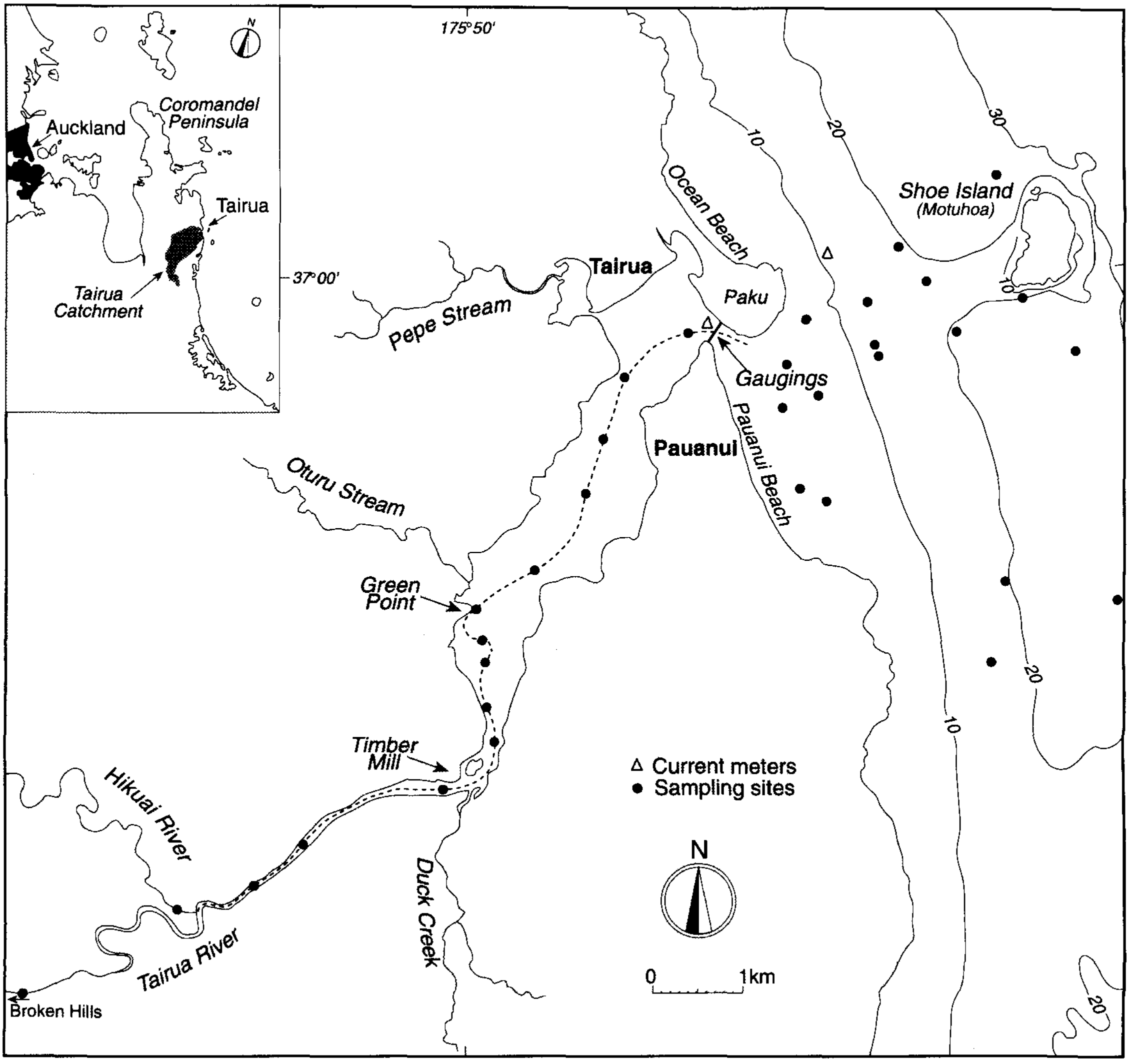

Fig. 1 Map of Tairua Harbour, North Island, New Zealand, with major river inputs and adjacent coastal waters; showing tidal gauging section, current meter positions, and sampling stations used in various surveys (except those used in the 12 June 1990 coastal survey, which are shown in Fig. 6). Depth contours in metres below Moturiki Datum (0.4 m below mean sea level).

Water samples were collected from the surface or pumped from depth (0.5–2 m) and transferred to polyethylene containers. These were immediately stored in ice chests until they could be refrigerated at 4°C for DSi samples, or frozen in the case of total phosphorus (TP) and total nitrogen (TN) samples. Laboratory analysis of DSi samples was usually undertaken within 36 h. Removal of particulate material, normally by filtration, before analysis for dissolved constituents is generally desirable (Liss 1976). To check on the validity of using unfiltered samples for Tairua, duplicate DSi samples were obtained at each of 11 sites during the spring survey (2 September 1985); one was filtered through a 0.45 μm Millipore filter within 2 h of sampling, and the other left unfiltered. An analysis of the small differences between unfiltered and filtered concentrations showed no obvious trend as a function of the concentration. The differences for the 11 samples (unfiltered minus filtered), were

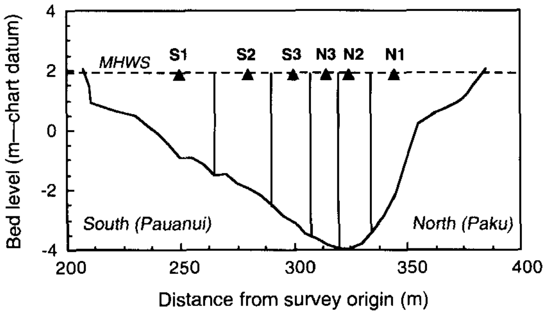

Fig. 2 Cross-section of Tairua Harbour entrance and the location of tidal gauging sampling sites (S = southern sites and N= northern sites). The vertical lines delineate flow sub-areas used to compute flows and solute fluxes using the mid-section method (Hume & Bell 1993).

evenly spread above and below zero with a mean of –3.4 µg Si l^{-1}. Using the statistical *t*-test, no significant difference exists, even at the 50% level, between the population means of the two pretreatments, implying no consistent uptake or production of DSi was derived from the particulate fraction before analysis.

The nutrient determinations were carried out using standard colorimetric methods on a Technicon Autoanalyser II system. In particular DSi concentrations were determined by the molybdenum blue method (Technicon 1977). Salinity (*S*) was determined by conductivity methods (practical salinity units) using either a field Yeo-Kal salinity meter (accuracy ± 0.05) and/or processing samples in a Yeo-Kal Model 602 salinometer (accuracy ± 0.005).

For the two tidal gauging surveys (Table 1), velocity was measured every half hour with a directional Braystoke current meter at three depths in the vertical (0.2, 0.6, and 0.8 of the total depth) and repeated at six stations across the tidal inlet channel (Fig. 2). DSi samples and salinity were taken concurrently at Sites S2 and N2. The tidal gauging technique used, and some of the velocity and discharge results for the Tairua spring tide gauging, are given in Hume & Bell (1993). Tidally-averaged Eulerian residual velocities $<\bar{u}_E>$ and fluxes, were calculated from interpolated values every 5 min (see Hume & Bell 1993), using the sign convention flood tide (–) and ebb tide (+). Two Aanderaa RCM4 recording current meters were deployed from 18 October to 24 November 1983, spanning the two tidal gaugings. One meter was placed in the tidal entrance, the other offshore Paku in about 10 m water depth, 4.5 m above the sea bed (Fig. 1).

RESULTS

Rivers

The results of limited DSi analyses of the two main rivers during field surveys over the study period are given in Table 2. The maximum DSi concentration in the Tairua River (9254 µg Si l^{-1}) occurred during the spring tide gauging on 8 November 1983, when the river flow of 18 $m^3 s^{-1}$ (twice the mean annual flow) was still high, following a large storm event the previous week. Otherwise DSi concentration was relatively constant in the range 8350–8800 µg Si l^{-1} for dry weather flows below the mean annual flow. The few DSi values in the smaller tributary, Hikuai River, were consistently higher than those in the Tairua River, with three of the samples falling in the range 10 600–11 600 µg Si l^{-1}. Riverine total phosphorus (TP) and total nitrogen (TN), measured during the estuarine survey of 30 May 1990, were low at 6–7 µg l^{-1} and 109–135 µg l^{-1}, respectively, in the Tairua River, reflecting the forested nature

Table 1 Various field surveys conducted in Tairua estuary (E) or adjacent coastal waters (C) between 1983–90. HW, high water; LW, low water; DSi, dissolved reactive silica; S, salinity; T, temperature; V, velocity; TP, total phosphorus; and TN, total nitrogen.

	Date	Season	Survey Type	Tide	Parameters measured
E	20/10/83	Spring	Tidal inlet gauging (13 h)	Neap	DSi, S, T, V
E	08/11/83	Spring	Tidal inlet gauging (13 h)	Spring	DSi, S, T, V
E	27/11/84	Spring	HW longitudinal survey	Spring	DSi, S, T
E	02/09/85	Spring	HW & LW surveys	Spring	DSi, S, T
C	11/12/85	Summer	LW samples 0 & 1.5 m	Spring	DSi, S, T
E	30/05/90	Winter	HW shoreline survey	Spring	DSi, S, T, TP, TN
C	12/06/90	Winter	LW samples 0 & 2 m	Neap	DSi, S, T, TP, TN

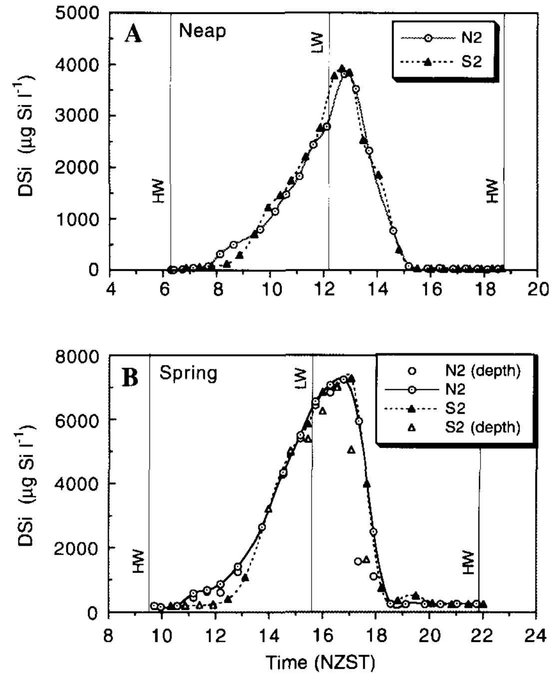

Fig. 3 Time series of DSi measured at Sites S2 and N2 for neap (**A**) and spring (**B**) tide gaugings.

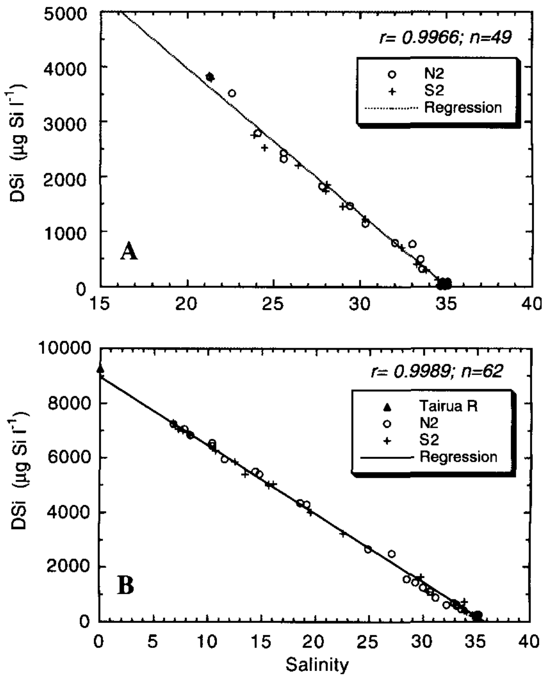

Fig. 4 DSi–salinity relationship for Sites S2 and N2 during neap (**A**) and spring (**B**) tidal gaugings.

of much of the hinterland. The higher TN concentrations occurred towards the estuary, probably owing to run-off from the pastured catchment adjacent to the lower reaches of the river.

Tidal entrance gaugings

The main aim of the tidal entrance gaugings was to quantify the tidal exchange of "old" estuarine water with "new" coastal water through the Tairua estuary entrance. Two full 13-hour tidal gaugings were carried out across the entrance channel for a neap and spring tide (Table 1). The DSi samples were only collected from two vertical stations, N2 and S2 (Fig. 2), which sampled the main bulk of the flow through the northern and southern halves of the entrance channel.

Table 2 DSi (μg Si l^{-1}) for *n* different surveys of the Tairua River and the main tributary, Hikuai River. (Up to 3 replicate samples for each survey were averaged).

River	*n*	Mean	Range
Tairua	6	8690	8344–9254
Hikuai	4	11630	10 593–13 430

Neap tide gauging (20 October 1983: Tide range = 1.25 m, Tairua R. flow = 7 m^3 s^{-1})

Based on velocity measurements, the maximum ebb and flood discharges through the entrance channel were 291 and –329 m^3 s^{-1}, respectively, and the neap tide prism was 4.0×10^6 m^3. The ebb tide flow duration of 6.6 h was slightly longer than the 5.9 h for the flood tide. The Eulerian residual velocity $< \bar{u}_E >$ at each station across the entrance channel influences the exchange of water with adjacent coastal waters and DSi residual fluxes. Depth profiles and the lateral distribution across the entrance channel of the derived Eulerian residual velocities are described in Hume & Bell (1993: fig. 6.1). The lateral pattern comprised a maximum flood-directed residual velocity (–8.6 cm s^{-1}) in mid-channel, flanked by ebb-directed residual velocities peaking at +8.0 and +12.5 cm s^{-1}, respectively, at each nearshore site (S1 and N1: Fig. 2). The typical residual (or net) depth-averaged salinity at each station was 32.4, with a difference of about 2 between the surface and the bed (Hume & Bell 1993: fig. 6.2). During the neap tide gauging, DSi samples were only collected from the surface waters at two sites, N2 and S2. The time series of the DSi concentrations over the tidal cycle are shown in Fig. 3A. The reversal of the tide (slack tide) occurred 40 min later than LW and coincided with the peak DSi values and a minimum salinity of 21.3. The distribution of DSi is highly correlated with salinity as shown in Fig. 4A, the linear relationship indicating conservative behaviour. The DSi fluxes through the entrance channel and tidal exchange are discussed below.

Spring tide gauging (08 November 1983: Tide range = 1.63 m, combined river flow = 18 m^3 s^{-1})

Based on the velocity measurements, the maximum ebb and flood discharges were 472 and −425 m^3 s^{-1}, respectively, and the spring tide prism was 6.1 × 10^6 m^3. Considerably more volume was exported during the ebb tide, compared to the flood tide, because of the higher river discharge; this was also the reason that the peak discharge was greater on the ebb rather than the flood tide, contrary to the neap tide gauging. Again because of the high river flow, the residual Eulerian velocity $< \bar{u}_E >$ was ebb-directed at all stations, ranging from +2.0 cm s^{-1} at Site N3 (mid-channel) to high values of +22 cm s^{-1} at both nearshore stations (S1 and N1: Fig. 2). The typical residual (or net) depth-averaged salinity (S = 28), was lower than that for the neap tide, with a difference of about 2.75 between the net salinity at the surface and the bed.

During the spring tide gauging, DSi samples were collected from both the surface waters and at depths up to 1.5 m, at the same two sites, N2 and S2, used previously. The time series of all the DSi concentrations over the tidal cycle are displayed in Fig. 3B. The regression of DSi concentration with salinity (Fig. 4B) for all 62 samples again shows a high correlation, indicating conservative mixing behaviour with sea water. In this case, extrapolation of the regression line to the river end member yields a slightly lower DSi concentration than the dominant fresh water input, Tairua River, suggesting that the main tributary (Hikuai River) had an even lower DSi content (unmeasured), contrary to the trend shown in Table 2. This may have resulted from the relatively high run-off in the previous week, causing differential erosion of different catchment rocks and soils, whereas all the other sampling runs were carried out for dry-weather river flows less than the mean annual discharge.

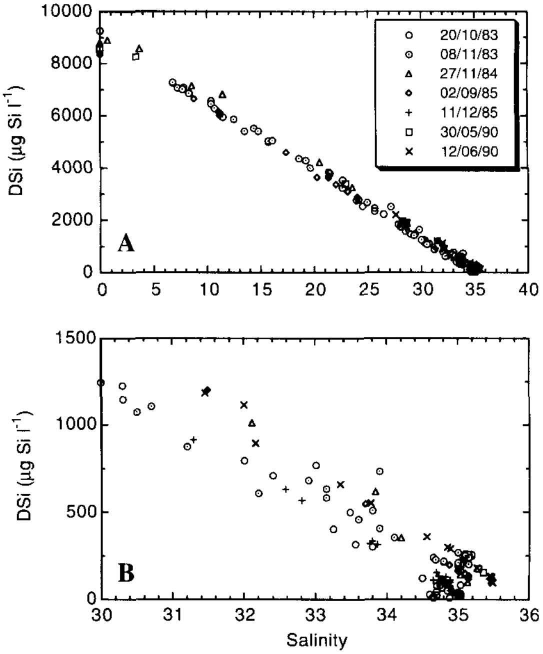

Fig. 5 DSi–salinity relationships for all seven estuarine and coastal surveys, for the entire salinity range (**A**), and a zoom plot for salinities > 30 (**B**).

Estuarine mixing

Correlation, slope, and intercept values for DSi concentration versus salinity regressions for each estuarine and coastal survey are listed in Table 3, and compared with actual river end member DSi concentrations. All data points from the seven surveys are also plotted in Fig. 5. Actual ocean end member salinities varied from 35.05 to 35.50, with corresponding DSi concentrations ranging from 10 to 195 µg Si l^{-1}. As expected, the DSi ocean end member does not fluctuate to the same extent, in absolute terms, as the river end member, which varied from 8615 to 9441 µg Si l^{-1} (range = 826 µg Si l^{-1}) based on regression intercept values (Table 3). DSi concentration in all surveys, which covered each of the seasons except autumn, exhibited very high correlations with salinity (Table 3), with the lowest coefficient r^2 = 0.993 during the neap tide entrance gauging (20 October 1983). The overall correlation coefficient of the pooled data was 0.996, which means the mixing behaviour of DSi in the Tairua estuary and adjacent coastal waters is essentially conservative, after allowing for sampling and analytical errors in both DSi and salinity. The longitudinal profiles of DSi concentration and salinity down the estuary (see sampling sites in Fig. 1) revealed mixing of low-salinity waters from the upper estuary, with marine water, normally occurs over the relatively short 2.7 km reach from south of the timber mill down to Green Point. This short reach marks the transition from a narrow confined channel (surface HW salinity < 10) to the wider intertidal estuary, where surface HW salinities down stream of Green Point are typically > 30.

Coastal waters

Two surveys (11 December 1985 and 12 June 1990) were specifically aimed at describing the distribution of DSi, salinity, and temperature in the coastal waters, covering the ebb tide plume from Tairua, coastal waters, and inner shelf waters out to 30 m depth. Again, the correlation of DSi concentration versus salinity was high (Table 3), involving samples from both the surface and near-surface layer down to 2 m depth. Contoured distributions of surface salinity, temperature, and DSi concentration are shown in Fig. 6 for the mean tide survey in June 1990. The outflowing plume from Tairua Harbour, at around LW, was advected north-east around the headland (Paku) and dispersed seaward on the surface towards the waters north of Shoe Island, under the influence of a northerly alongshore current and a 10–15 knot south-east wind. Salinities at 2 m depth (see dotted contours on Fig. 6A) revealed that the main sub-surface extension of the ebb plume was much narrower and heading in a north-northeast direction. In the earlier 1985 spring tide survey, the ebb jet was transported due east towards Shoe Island, before turning north-east, under a weaker northerly alongshore current. Low DSi levels (< 50 μg Si l^{-1}) were found around Shoe Island, indicating oceanic waters were found at the 30 m contour. At the southern end of Pauanui Beach (Fig. 1), DSi measured around 80 μg Si l^{-1}. However offshore, east of the nearby southern headland, in a parcel of surface water at the 20 m depth contour, DSi concentration reached twice this value (150 μg Si l^{-1}) accompanied by a decrease in salinity of 0.17: probably a remnant water mass derived from a run-off source further south. Other nutrients measured at each coastal site in the 12 June 1990 survey (TP and TN) did not reveal any distinct spatial patterns, with concentrations tightly clustered about the mean TP and TN concentrations of 12 and 96 μg l^{-1}, respectively.

Tidal exchange

A portion of the volume of water entering an estuary during a flood tide comprises water that left the estuary on previous ebb tides. The remainder is water that we may think of as "new" oceanic water, and since this portion is what is available for dilution of pollutants discharged inside the estuary, an estimate of the tidal exchange ratio is often a key parameter. Time series of velocities and concentrations of both tracers, DSi and salinity, from the neap and spring tidal gaugings, were used to derive estimates of the exchange ratio. This ratio (R_E), in its simplest form, is the proportion of "new" ocean water flowing in on a flood tide to the total incoming volume, comprising both "new" ocean water and "old" estuarine water, and therefore ranges from 0

Table 3 DSi versus salinity (S) regression results for the seven surveys at Tairua (1983–90) in the form: DSi (μg Si l^{-1}) = DSi$_0$ + a S. Note: the average flow in Hikuai River was about 19% of the flow in the main Tairua River.

Date	No. samples (n)	Correlation coeff. (r^2)	Slope (a)	Intercept (DSi$_0$)	River end member (DSi)	
					Tairua R	Hikuai R
20/10/83	49	0.993	−265.3	9285	–	–
08/11/83	62	0.997	−250.9	8967	9254	–
27/11/84	11	0.997	−263.0	9441	8806	10593
02/09/85	20	0.999	−247.3	8840	8344	10884
11/12/85	32	0.996	−244.9	8615	8474	13430
30/05/90	6	1.00	−253.2	9123	8547	11621
12/06/90	21	0.997	−257.3	9248	–	–
All data	201	0.996	−253.4	8992		

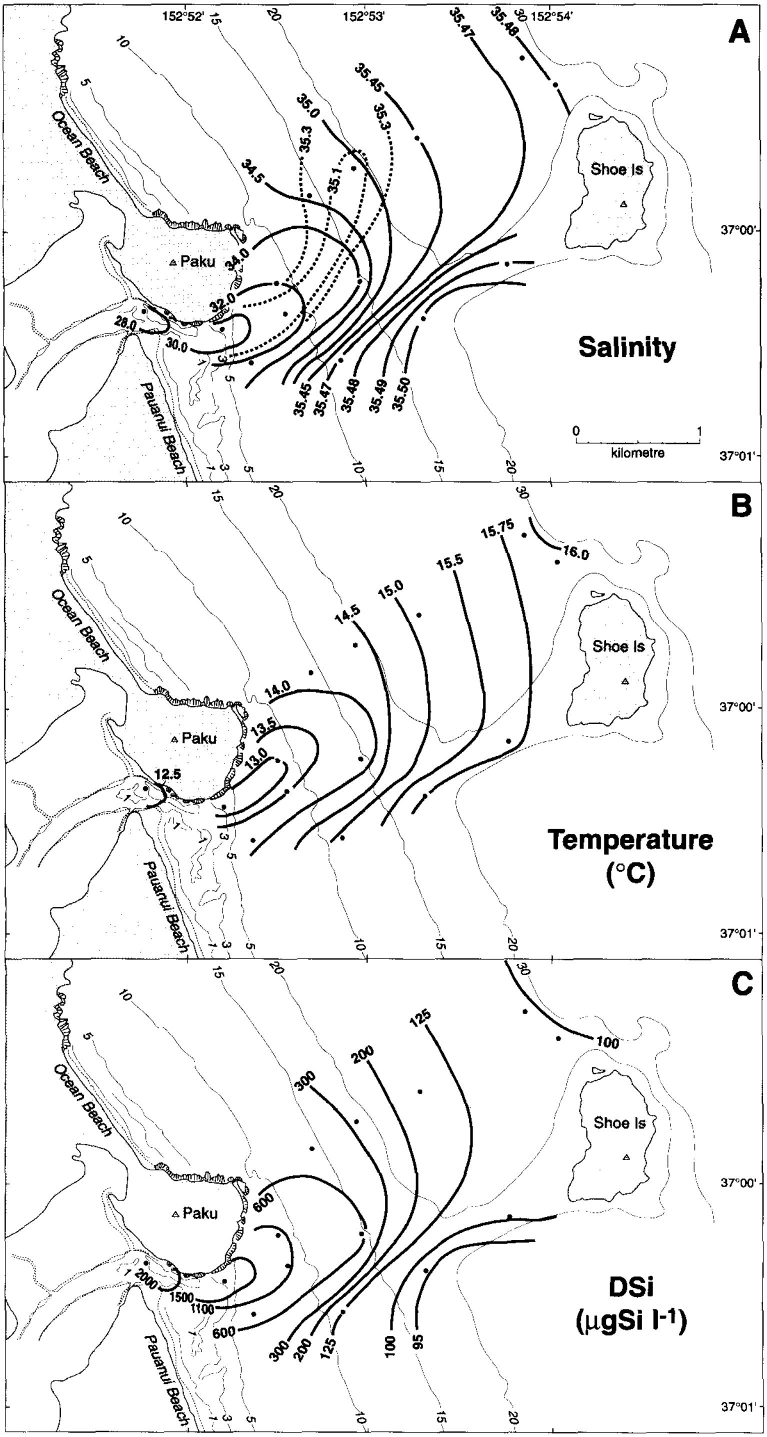

Fig. 6 Ebb tide jet distributions around LW on 12 June 1990 for **A**, salinity; **B**, temperature (°C); and **C**, DSi (µg Si l^{-1}).

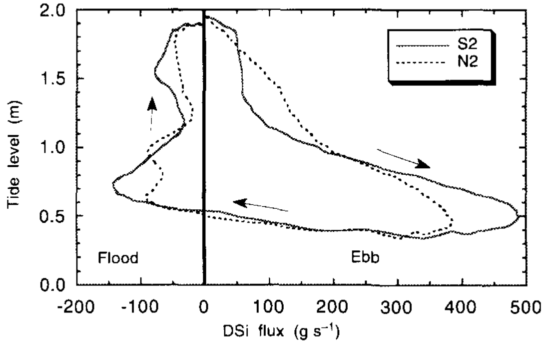

Fig. 7 Ebb and flood tide DSi fluxes (g s^{-1}) at various stages of the tide level for Sites S2 and N2 during the spring tidal gauging (8 November 1983). (The mismatch for zero flux at HW results from the diurnal inequality of successive high waters).

(no exchange) to 1 (complete exchange). The tidal exchange ratio can be defined (Parker et al. 1972):

$$R_E = \frac{\overline{C}_f - \overline{C}_e}{C_o - \overline{C}_e} \qquad (1)$$

where $\overline{C}_f$ and $\overline{C}_e$ are the weighted average tracer concentrations or salinities for the flood and ebb tide flows, respectively, and C_o is the solute concentration or salinity of the ocean water. The weighted average tracer concentration over the flood tide is defined by

$$\overline{C}_f = \sum_{i=1}^{n} Q_{fi} C_{fi} \Delta t \Big/ \sum_{i=1}^{n} Q_{fi} \Delta t \qquad (2)$$

where Q_{fi} and C_{fi} are the flood tide discharge and tracer concentration in time increment i, Δt is the time increment and n is the number of time increments in the flood tide phase. $\overline{C}_e$ on the ebb tide can similarly be computed. (Note: other researchers, e.g., Webb & Tomlinson (1992), use an alternative exchange coefficient $E = 1 - R_E$.)

The methods used to calculate flood and ebb solute fluxes (mass per time) through the tidal entrance cross-section and net (i.e., tidally-averaged) fluxes and volumes are described in detail by Hume & Bell (1993). The resulting hysteresis pattern in DSi fluxes with tide level through the northern (N) sites and southern (S) sites sections of the entrance channel are shown for the spring tide gauging in Fig. 7. The peak DSi efflux occurred just before low water when—although ebb tidal velocities had decreased—DSi concentrations increased markedly (Fig. 3B) as less diluted riverine water reached the entrance. The most striking feature of these flux distributions is the large net export of DSi, which is also acting as a tracer of a potential catchment-derived constituent. The net tidal cycle export of DSi on the spring tide (higher river flow) was 7800 kg Si, whereas the corresponding value for the neap tide gauging was 1900 kg Si. A tidal exchange ratio can also be taken as one minus the ratio of the time-integrated DSi mass inflow on the flood tide to the previous ebb tide mass outflow. The final method used to determine tidal exchange was to compare the fresh water fraction volume in both the flood and ebb flows. Based on the salinity S of derived water volume flowing through each subsection of the entrance channel every 5 min, the fresh water fraction (F) sub-volume is defined (e.g., Fischer et al. 1979):

$$F = \frac{S_o - S}{S_o} \qquad (3)$$

where S_o is the ocean salinity.

The derived tidal exchange ratios for both the neap and spring tide gaugings, based on salinity and DSi measurements, are listed in Table 4. The high values indicate that relatively efficient tidal exchange of Tairua Harbour waters occurred, irrespective of tide range.

DISCUSSION

River inputs

Mean values of DSi concentration (based on limited sampling) in the Tairua River (8690 µg Si l^{-1}) and its tributary, Hikuai River (11 630 µg Si l^{-1}), are consistent with generally high published DSi levels for New Zealand rivers (e.g., Bradford 1983; Bryers 1985; Taylor & Taylor 1985), which are usually above 8000 µg Si l^{-1}. The known exception is the

Table 4 Tidal exchange ratios, expressed as percentages, for Tairua Harbour entrance, based on salinity and DSi concentrations, for the neap (20 Oct 1983) and the following spring (8 Nov 1983) tidal gaugings.

Method	Neap tide	Spring tide
Average salinities (Eq. 1)	83%	81%
F for ebb and flood vols. (Eq. 3)	83%	87%
Average DSi (Eq. 1)	82%	83%
DSi flood/ebb fluxes	79%	79%

Otago region (Grundy 1985; Hunter & Tyler 1987), where concentrations are often low, in the range 350–7000 μg Si l^{-1}, and fluctuate considerably with river discharge and between seasons. The generally high DSi concentrations for New Zealand rivers, compared to world-wide levels (Meybeck 1979), also enhance the usefulness of DSi as a tracer of river water (or other catchment solute) in estuarine and coastal waters, provided DSi behaves conservatively. The distinct difference in DSi concentration between the two rivers (Tairua and *Hikuai)* in this instance, and their combined well-mixed concentration further down stream, can also be utilised in a simple dilution method to estimate the relative contributions of catchment flows to an estuary or main river, adapting the method of Hunt & Foster (1977).

The definition of the river end member (including temporal variation) is crucial, when using theoretical dilution (or mixing) curves for estuarine mixing (Loder & Reichard 1981). Studies of estuarine mixing need to be supported by regular measurements of the major fresh water inputs over a time period of several residence times of the estuary, as demonstrated by the considerable weekly variability in DSi concentrations of Otago rivers by Grundy (1985) and Hunter & Tyler (1987). For the Tairua system, the extrapolated river end-member concentration of DSi was reasonably close to the combined flow-weighted DSi measurements of the two major rivers in each instance (inferred from Table 3). This apparent agreement is perhaps fortuitous, given the very limited river sampling before each estuarine/coastal survey, largely because of the short residence time of Tairua Harbour and that most of the fresh water input to Tairua Harbour enters from up stream of the upper estuary. Therefore complications may arise using dilution (mixing) curves in estuaries where the freshwater DSi is inadequately sampled over time, relative to the estuary flushing time, and where significant tributaries or bank run-off occurs throughout the estuary.

Estuarine and coastal mixing

In all surveys, the very high correlations between DSi and salinity (Fig. 5) and the close fit to a linear relationship suggest that dilution is the only process having any effect on the distribution of DSi in both estuarine and coastal waters at Tairua. Thus DSi can be regarded as behaving conservatively and therefore could be used as an alternative tracer of water masses in both estuarine and coastal waters at Tairua. Burton et al. (1970) found similar high correlations for DSi versus salinity ($0.97 \leq r \leq 1.00$) for several surveys of Southampton Water. Several other researchers (summarised by Blanchard (1988)) also found conservative behaviour of DSi in various estuarine systems, or alternatively, a small level of removal, thus indicating that removal of DSi is often a relatively minor process affecting DSi distribution relative to physical dilution. In Tairua Harbour, the conservative behaviour of DSi is not unexpected, as river water has a short residence time in the estuary, before being exported to coastal waters. The short solute residence time in the estuary and high exchange rate with coastal waters (particularly where an alongshore current is present) allow relatively little time for other biochemical processes to act, such as biological uptake by phytoplankton. Thus estuarine circulation, driven primarily by tidal forcing and river flow, dominates the mixing and distribution of DSi (and other nutrients) in Tairua Harbour.

A comparison of DSi around the most offshore sites around Shoe Island (Fig. 6), only 3 km off Paku, was made with DSi obtained in two previous New Zealand coastal/oceanic studies off Westland (Bradford 1983) and South Otago (Hawke 1989), where both areas are affected by major river outlets. The low levels of DSi (50–100 μg Si l^{-1}) obtained around Shoe Island, are consistent with inshore surface concentrations obtained in both previous studies, out of the zone of river influence. These low levels (and the salinities) at Shoe Island are indicative of oceanic waters, which implies complete mixing of fresh water (under normal flow conditions) and riverine solutes occurs over a relatively narrow coastal zone (2–3 km) along this stretch of the Coromandel. This results from the relatively small freshwater run-off volumes and moderate alongshore currents, often 15–30 cm s^{-1} off Paku, which alternate up- or down-coast at 2–5-day intervals, most likely the result of coastally trapped waves. Unlike in South Otago waters, where Hawke (1989) found that only the winter surveys demonstrated conservative DSi behaviour, summer and winter coastal surveys off Tairua both indicated conservative behaviour.

It often happens that the same physical or chemical property can be measured in different ways; in this case the tracing of river mixing with marine waters by both DSi and the freshwater fraction (via salinity). If only one tracer is required, the question arises, Which method is better? The main interest, then, is the precision (or reproducibility) of the two measurements. Comparing methods x and y that are expressed in different units, yields a sensitivity ratio of y with respect to x (Mandel 1991)

$$S_{y/x} = \frac{\Delta y / \Delta x}{\sigma_y / \sigma_x} \tag{4}$$

where $\Delta y/\Delta x$ represents the slope of the regression curve, and the denominator is the ratio of the standard deviations of reproducibility for the two methods. Based on typical values of the standard deviation of replicate analyses/measurements for DSi (10 µg Si l^{-1}) and salinity (0.05), using a field salinity meter, the derived sensitivity ratio is around unity, indicating a similar sensitivity for both methods. Both methods therefore have the same precision, but salinity has the advantages of ease of measurement, ready interpretation in the field, and is usually cheaper than laboratory analyses. (The use of a more accurate salinometer would improve the sensitivity of the freshwater fraction method, although in practice sample reproducibility is limited in estuaries by small-scale temporal and spatial fluctuations in salinity, and the net result may be little improvement). However in studies of coastal and oceanic waters, additional conservative natural tracers, besides salinity and heat content (temperature), are often required to isolate distinguishable coastal water masses from various sources. Often DSi is suitable for this purpose, and sometimes other nutrients (e.g., Hunt & Foster 1977; Mackas et al. 1987). The fact that, in this instance, DSi and salinity yielded similar tidal exchange ratios for Tairua Harbour entrance (Table 4) confirms that they can both be used as valid tracers of fresh water.

Tidal entrance inflows/outflows

The main feature of the neap and spring tide time series (Fig. 3), is the rapid reduction in DSi concentrations during the first 1.25–2.0 h of the incoming (flood) tide. The incoming flux initially comprised "old", lower-salinity, estuarine water, released during the latter period of the previous ebb tide, but this was rapidly replaced by the influx of "new" coastal water, marked by high salinity ($S = 35$) and low DSi concentrations (15–30 µg Si l^{-1} for the neap tide and 230–260 µg Si l^{-1} for the spring tide). This rapid onset of incoming "new" coastal water is reflected in the high exchange ratios (Table 4). The larger DSi concentrations in the local coastal waters for the spring tide were due to the large freshwater run-off from the catchment, which peaked 9 days before the gauging, when a minimum coastal salinity of 30.7 was recorded by the current meter off Paku at a depth of 6 m. Longer lag times between LW and the peak DSi values were obtained for the spring tide, compared to the neap tide, which is also mainly attributable to the larger river flow (twice the mean annual flow) through the estuary. This generated a stronger net (or tidally-averaged) outflow at the surface, and vertical salinity differences of up to 3, between the surface and the bottom. This compares with the DSi for the deeper samples shown in Fig. 3B, which declined earlier than their surface counterparts, owing to the incoming saline water sliding underneath the outgoing brackish water for a period of 1.2 h around slack tide. Subsequently, the decline of surface DSi in the incoming flood tide flow occurred dramatically over a short period of little over 1 h between 1700–1800 NZST (Fig. 3B), as "new" water was drawn in from surrounding nearshore coastal waters.

Small differences in DSi concentration (Fig. 3) occurred between the two sampling sites (N2 and S2) at any one time. However no grouping patterns could be distinguished between Sites N2 and S2, based on the DSi-salinity regression (Fig. 4). Therefore lateral variability in DSi concentration (besides analytical/sampling uncertainties), can be attributed to a transverse variation in salinity across the section, i.e., the overall water composition through each section differs slightly, particularly on the ebb tide. This reinforces the importance that adequate lateral coverage of both velocity and solute fluxes is achieved in entrance tidal gaugings to ensure net or residual fluxes are reliable (Kjerfve & Proehl 1979; Kjerfve et al. 1981; Hume & Bell 1993). The high correlation of DSi concentration with salinity (Fig. 4) indicates that DSi is behaving conservatively, both in the ebb and flood flows, through the entrance. This was during the middle of spring (which is often the period of rapid diatom growth), and covered both a mean annual and a high river flow.

Tidal exchange

Closely spaced contours of surface salinity, temperature, and DSi concentration at the southern sites (Fig. 6), tending perpendicular to the coastline, are indicative of a sharp frontal region. This divides the lower-salinity ebb tide jet from the "new" coastal waters flowing into the Pauanui embayment from the south during the survey period. The role

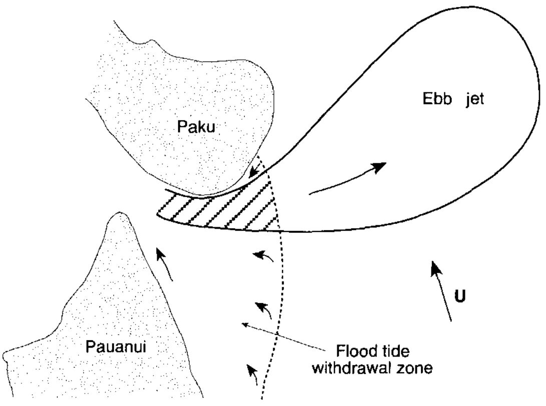

Fig. 8 Schematic of coastal flow asymmetry for ebb and flood tide phases off the Tairua Harbour entrance for a northerly flowing alongshore current (U). The hatched area denotes water that is returned on the subsequent flood tide. The larger velocity vector along Pauanui Beach indicates the flood-dominated secondary channel flow between the beach and the ebb tidal delta.

of the alongshore current is to deflect the ebb jet downcoast and deliver the supply of "new" ocean water from upcoast for the flood tide inflow, as shown schematically in Fig. 8. Therefore the prevailing alongshore coastal current, provided it is not overly strong causing re-attachment to the coast, becomes a very efficient mechanism for the ultimate exchange of estuarine water and DSi with the offshore coastal waters. In the absence of an alongshore current, all of the exchange would be by relatively inefficient local mixing processes in the coastal zone (Fischer et al. 1979).

Published values of tidal exchange ratios for both water and nutrient masses, vary considerably for various tidal inlet/estuary systems. Examples at each extreme range from a low exchange ratio of 4–10% for the Grådyb tidal area in Denmark (Pejrup et al. 1993), to a high value of 88% for Peel Inlet in Australia (Black et al. 1981). In this context, the exchange mechanism off Tairua (R_E = 82%) is very efficient, and is probably assisted by flow modification of the alongshore current resulting from the offset between Paku headland and the Pauanui barrier, as shown in Fig. 8. The exchange ratios for Tairua Harbour entrance are remarkably similar for both the neap and spring tide gaugings. This is in contrast to the exchange studies on larger harbours, (e.g., Parker et al. 1972; Charlton 1980), where the exchange ratio increased with tidal range, owing to the larger volume of water drawn into the harbours on a flood tide over a wide flood withdrawal zone, and hence a larger fraction of "new" water is expected. As mentioned above, the alongshore current and planform geometry of the Tairua coastline control the exchange mechanism, and seem to overide any effect of the relatively small flood tide prism required for the estuary. Charlton (1980) used a numerical hydrodynamic model of the Tay Estuary (Scotland) to investigate the effect of different river discharges on the tidal exchange ratio, and found that the exchange was largely tidally controlled, with little change due to river discharge. This also appears to be the situation for Tairua, where the spring tide gauging, for a river flow roughly twice the mean annual discharge, yielded similar exchange ratios as those obtained for a neap tide with a much lower river discharge (Table 4). The tidal exchange ratios at Tairua also compare favourably with predicted values of 81% (neap) and 83% (spring), using the steady jet numerical model (with entrainment) of Özsoy (1977), which is further described by Webb & Tomlinson (1992).

A further salient feature of the tidal gauging results is the lateral variability in tidal exchange ratio across the entrance channel. For the neap tide, the range for the six measurement stations (Fig. 2) was $76\% < R_E < 90\%$, and for the spring tide, $55\% < R_E < 87\%$, with the lower exchange ratios occurring at the southern two sites (S1 and S2: Fig. 2). This is consistent with the extension of the flood tide withdrawal zone to the south along Pauanui Beach (Fig. 8), and the existence of a flood-dominant secondary channel running between the tip of the Pauanui barrier and the ebb tide delta. This lateral variability highlights the need for adequate coverage of both the water flow and solute measurements in a tidal entrance to ensure that realistic net fluxes and tidal exchange ratios are obtained.

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