River inputs, re-mineralisation and the spatial and temporal distribution of inorganic nutrients in Tasman Bay, New Zealand

LINCOLN MACKENZIE
Cawthron Institute
Private Bag 2
Nelson, New Zealand
e-mail: Lincoln.Mackenzie@cawthron.org.nz

Abstract To improve understanding of the temporal and spatial variability of biological productivity relevant to fisheries enhancement within Tasman Bay, New Zealand, it is necessary to evaluate the importance of variations in river inflows on inorganic nutrient dynamics. To achieve this, a series of synoptic surveys of surface and water column salinity fields and inorganic nutrient concentrations were carried out over a 1-year period, at seasonally representative times, during, and soon after, a range of flow regimes in the major freshwater tributaries of Tasman Bay. An assessment was made of the relative importance of external (i.e., river borne) and internal (i.e., recycling) nutrient sources that control the fertility of the Tasman Bay water column. Flood events in the bay’s catchment cause significant changes in the levels of dissolved nitrogen, phosphorus, and silica in surface waters, and on an annual basis 60–70% of the input of “new” dissolved inorganic nitrogen from freshwater tributaries is contributed by the Motueka River. As a consequence there is a pronounced east to west gradient in nutrient enrichment, and oceanic water most frequently intrudes along the eastern shore. Surface salinity and inorganic nutrient distribution patterns and inferred water movements are consistent with the left hand deflection of buoyant river plumes. The predictable timing and magnitude of the winter nitrate/nitrite maxima suggests that light is the main factor limiting phytoplankton production and nutrient assimilation during the winter, and that benthic and pelagic re-mineralisation processes are the dominant mechanism generating the annual nutrient maxima within the water column as a whole. Calculations suggest that the net accumulation of inorganic nitrogen via endogenous re-mineralisation over the autumn–winter period is of a similar order of magnitude to the annual introduction of new nitrogen from freshwater sources. How this compares to inputs of new nitrogen by advection from oceanic sources has yet to be determined.

Keywords Tasman Bay; inorganic nutrients; river inputs; re-mineralisation

INTRODUCTION The waters and sea floor of Tasman Bay, New Zealand (Fig. 1) are an important regional and national resource with a variety of amenity and economic values which depend upon the maintenance of a high standard of environmental quality. Within the large (3876 km²) watershed of the bay are extensive horticultural, forestry, and pastoral industries. The bay receives water from several rivers, the largest of which is the Mouteka River with a catchment of 2180 km² (Basher 2003). There are two main urban centres (total population c. 60 000) which discharge treated sewage, untreated storm water, and waste water from fish processing factories. All these activities may conflict with the maintenance of a high standard of water quality within the bay which supports important coastal fisheries and shell-fisheries including a valuable scallop (Pecten novaezelanidæ) re-seeding and enhancement industry, established in the early 1980s. At present long-line aquaculture is prohibited in Tasman Bay, though seasonal scallop and mussel spat catching is permitted, and large areas offshore of the Motueka River mouth have been designated as an “Aquaculture Management Area” for future development as a mussel growing region.

Because of their intrinsic value, and evidence that suggests human activity is having a significant impact on nutrient inputs and biogeochemical cycling within these ecosystems, there is an
Fig. 1  A, Geographic location of Tasman Bay, New Zealand, and major freshwater inputs, bathymetry; and B, location of sample survey sites and transects. Sites 1B (“Glen”), 4B (“Ruby Bay”), and 7B (“Bomber”) were used for routine long-term monitoring. “Pitt Head” and “Pepin Is.” and 30 m contour boundaries define the limits of the study area.
increasing level of international concern about the health of shallow coastal seas like Tasman Bay (Justic et al. 1987; Hickel et al. 1993; Jickells 1998; Rabalais et al. 2002). In particular, changes in the magnitude and relative abundance of inorganic nitrogen, phosphorus, and silicon in the freshwater inputs to coastal seas are believed to have the most important effects (Justic et al. 1995). It is these elements, in concert with the availability of light and trace elements and the effect of hydrodynamic factors, upon which the nature and productivity of the phytoplankton and hence most benthic and pelagic biomass production is critically dependant. Within this context, Tasman Bay is a typical shallow (mean depth 30 m) Southern Hemisphere embayment which has been transformed from a pristine wilderness to an increasingly intensively exploited environment within the last 150 years of European settlement.

There are few published accounts of the water movements within the bay and most of these are rather old (Heath 1973, 1976, 1979; Ridgway 1977). These studies identified currents within the bay as being mainly tidally driven with surface flows being strongly influenced by wind speed and direction and inferred (from drift card distributions) that the mean circulation is characterised by a counter clockwise flow. These studies were the first to identify that surface temperatures and salinity are significantly affected by insolation and coastal run-off. More recently published current meter measurements made at one site off the Motueka River mouth (Gibbs 2001) have shown near bottom tidally driven current velocities of 5–15 cm s\(^{-1}\). A hydrodynamic model of the circulation within Tasman and Golden Bays is under development (Tuckey et al. 2003) and although it is able to simulate wind generated and tidally forced water flows within the bays it has yet to be fully validated. Using this model, a preliminary estimate (using a mean residual current speed of 3.5 cm s\(^{-1}\) and no wind) of the water exchange time for the area of Tasman Bay bounded by Cape Soucis and Separation Point (Fig. 1) is 72 days (Tuckey pers. comm.). Heath (1973) estimated a water exchange time of 63 days for the entire Tasman and Golden Bay region, assuming a north-west wind speed of 8 m s\(^{-1}\) and surface current velocity of 7 cm s\(^{-1}\).

Previous published data on the hydrography, nutrient chemistry, plankton ecology, and productivity of the bay include a study by MacKenzie & Gillespie (1986) who sampled a single site (10 m depth) at c. 1-month intervals over a 2-year period between 1982 and 1984. They found that the water column at the sampling site was strongly stratified because of temperature and salinity gradients for most of the year, and that the phytoplankton phenology was typical of a temperate neritic environment with considerable year-to-year variation in specific composition and the magnitude of production. They identified the winter/spring diatom bloom as the most productive annual event and suggested that the magnitude of this bloom was related to preceding high rainfall episodes. Although some synoptic sampling was carried out during the course of this study, spatial coverage was limited. Field studies by Bradford et al. (1986) included several Tasman Bay sites within intensive summertime synoptic surveys (1980–81) of the hydrography, nutrient chemistry, and plankton ecology of greater Cook Strait. There has been the sporadic collection of water quality data at monitoring stations coincident with the scallop enhancement zones and some of these are presented here.

In 1994, a report was prepared to summarise the state of knowledge of the Nelson Bays marine environment relevant to fisheries enhancement (Bradford-Grieve et al. 1994) and to identify future research needs. This report highlighted a general lack of understanding of how the different parts of the benthic and pelagic food-webs within the bay interact with one another and the impact of the physical environment on these interactions. In particular, the review identified the need to undertake research to examine the effect of variations in river flows on stratification and nutrient concentrations. It was believed this was crucial to an understanding of the temporal and spatial variability of biological productivity relevant to the sustainability of fisheries enhancement and it was recommended that detailed spatial and temporal surveys of the bay be carried out. The results and interpretation of the surveys subsequently carried out as a consequence of this recommendation are recounted here and are augmented with long-term monitoring data collected on behalf of the shellfish industry at three sites in Tasman Bay. The results of observations on the spatial and temporal distribution of phytoplankton biomass relative to water column stratification that were made concurrently with those presented in this paper are contained in MacKenzie & Adamson (2004). Water column stratification characteristics greatly effect inorganic nutrient distributions, and examination of the data presented in the companion paper with the data presented here is essential to obtain a fuller understanding of the nutrient
dynamics of the system. The focus of this paper is a comparative evaluation of the processes of internal recycling and land drainage as nutrient sources within the study area. It does not directly address the contribution made by oceanic advection as a source of inorganic nutrients because as yet there is insufficient data available on which a perspective on the magnitude of this source may be gained.

METHODS

Sampling

Synoptic surveys were carried out by sampling 44 stations along five east/west and nine north/south transects across Tasman Bay (Fig. 1) between October 1995 and October 1996. The sampling stations were aligned c. 5 km apart along non linear transects (A, B, B', C, D) which followed the 30, 20, 15, 10, and 5 m below chart datum (LAT) contours respectively. Parts of Tasman Bay experience the highest tidal ranges in New Zealand (up to 5.1 m mean high water spring), so the actual depth at the time of sampling varied somewhat. Site 3C was at approximately the same location as the main study site (site 2) of MacKenzie & Gillespie (1986). The sampling sites were located to an accuracy of ±100 m using a Trimble “Pathfinder” GPS system. All surveys were carried out over two consecutive days with the three inshore transects (B’, C, D) being sampled on day one and the seaward transects (A, B) on day two; sampling was accomplished in 5–6 h on both occasions. At each station a surface water sample was collected for the analysis of dissolved inorganic nutrients, and water column profiles of salinity, temperature, and chlorophyll fluorescence were obtained using a Chelsea Instruments “Aquapak” conductivity-temperature-depth/fluorometer. The fluorometer was calibrated by extraction of phytoplankton pigments. One-litre volumes were filtered (GFC) and extracted in 90% acetone before spectrophotometric determination of chlorophyll a (Chl. a) concentrations using the equations of Jeffrey & Humphery (1975). At three stations along transect B (1B, 4B, 7B), at locations representative of east, mid, and west areas, van Dorn water bottle casts were made to obtain samples for dissolved inorganic nutrients analyses, at 5 m intervals from the surface to 1 m from the sea floor. At each station along transect 7 (Fig. 1B) off the mouth of the Motueka River, water samples were also collected at the same depths plus an additional sample at 2.5 m to include the subsurface river-plume water. Eleven surveys were carried out between 3 October 1995 and 9 October 1996. Sampling surveys were carried out during and subsequent to a variety of flow regimes in the Tasman Bay rivers (Fig. 2B, Table 1). The first four occasions were at 13–19-day intervals during the spring (October–November) 1995 during and after a series of major flood events. Subsequent surveys were carried out at 1–2-month intervals. During the midwinter and spring months in 1996, weekly measurements of inorganic nutrients and phytoplankton biomass within the water column at the two routine monitoring sites (4B and 7B) were made in an attempt to capture a more detailed picture of the sequence of events accompanying the development and decline of the spring bloom. At various times during the early to mid 1980s, monitoring stations within the scallop enhancement regions of Tasman Bay were activated in an attempt to identify the cause of periodic scallop mortalities. These stations were respectively referred to as sites “Glen”, “Ruby Bay”, and “Bomber” and correspond to the survey sites 1B, 4B, and 7B respectively (Fig. 1B). On each occasion samples were collected from the surface mid water and near the bottom. These

![Fig. 2 A](#) Relative magnitude (m³ x 10⁹ year⁻¹) of the total annual discharge during 1995 and 1996; and B, (opposite) combined total daily flows (m³ x 10⁶ day⁻¹) in the Motueka, Riwaka, Waimea, and Maitai Rivers, New Zealand, during the sampling survey period. Arrows represent the sample survey occasions.
Table 1  Timing of sampling surveys relative to recent river flows in the Motueka River, New Zealand.

<table>
<thead>
<tr>
<th>Date</th>
<th>Daily mean flows (corrected for catchment size)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 Oct 1995</td>
<td>Coincided with moderate-high river flows (187 m$^3$ s$^{-1}$ daily mean) and was preceded 3 and 6 days before by two major flood peaks (422 and 452 m$^3$ s$^{-1}$).</td>
</tr>
<tr>
<td>20 Oct 1995</td>
<td>Coincided with declining moderate river flows (102 m$^3$ s$^{-1}$) from a flood peak (416 m$^3$ s$^{-1}$) 5 days before.</td>
</tr>
<tr>
<td>3 Nov 1995</td>
<td>Coincided with a moderate size flood peak (131 m$^3$ s$^{-1}$) low flow during preceding 14 days.</td>
</tr>
<tr>
<td>22 Nov 1995</td>
<td>Low flow (38 m$^3$ s$^{-1}$), 11 days since previous moderate flood peak (140 m$^3$ s$^{-1}$).</td>
</tr>
<tr>
<td>9 Jan 1996</td>
<td>Low flow (27 m$^3$ s$^{-1}$), 10 days after last moderate (166 m$^3$ s$^{-1}$) flood peak and 16 days after last major flood peak (715 m$^3$ s$^{-1}$).</td>
</tr>
<tr>
<td>22 Feb 1996</td>
<td>Declining low-moderate flow (50 m$^3$ s$^{-1}$), preceded 2 days before by moderate flood peak (190 m$^3$ s$^{-1}$).</td>
</tr>
<tr>
<td>26 Mar 1996</td>
<td>Declining low-moderate flow (49 m$^3$ s$^{-1}$), preceded 3 days before by moderate flood peak (138 m$^3$ s$^{-1}$).</td>
</tr>
<tr>
<td>15 May 1996</td>
<td>Low flow (26 m$^3$ s$^{-1}$), 30 days since last moderate-high flood peak (215 m$^3$ s$^{-1}$).</td>
</tr>
<tr>
<td>19 Jul 1996</td>
<td>High flow (154 m$^3$ s$^{-1}$), 3 days after major flood peak (409 m$^3$ s$^{-1}$).</td>
</tr>
<tr>
<td>28 Aug 1996</td>
<td>Moderate flow (80 m$^3$ s$^{-1}$), 7 days after major flood peak (345 m$^3$ s$^{-1}$).</td>
</tr>
<tr>
<td>9 Oct 1996</td>
<td>Coincided with moderate flood peak (137 m$^3$ s$^{-1}$), 1 day after maximum flow (237 m$^3$ s$^{-1}$).</td>
</tr>
</tbody>
</table>

sites were not always sampled simultaneously as this was dictated by whether that particular region was re-seeded with juvenile scallops at the time. The data presented from this sampling (Fig. 6) therefore is a composite of the data from these three sites, not all of which were sampled on each occasion.

**Nutrient analyses**

Samples for ammonium (NH$_4^+$-N) analysis were dispensed into acid-cleaned sample bottles and immediately chilled on ice then filtered and frozen within 3–4 h of collection. Water samples for nitrate (NO$_3^-$-N), nitrite (NO$_2^-$-N), dissolved reactive phosphorus (DRP), and dissolved reactive silicate (DRSi) analyses were preserved with 1 ml/litre of 2% HgCl$_2$ immediately after collection, filtered (GFC), and the samples refrigerated before analysis (Kattner 1999). The phenol hypochlorite method of Solarzano (1969) was used for the analysis of NH$_4^+$-N. NO$_3^-$-N and NO$_2^-$-N were determined colorimetrically (Strickland & Parsons 1968), the former after cadmium column reduction and DRP and DRSi were analysed by the ascorbic acid/ammonium molybdate and metol-sulphite/ammonium molybdate methods respectively (APHA 1980). All the nutrient analyses reported here are expressed as elemental (i.e., N, P, and Si) mmol m$^{-3}$ (= µg atoms litre$^{-1}$) concentrations. All three-dimensional data were
plotted using Golden Software’s “Surfer” (version 6.01) surface mapping program using Kriging as a gridding method.

Tasman Bay receives fresh water from four major rivers, the Motueka and Riwaka Rivers on the western side of the bay, and the Waimea and Maitai Rivers entering through tidal sand/mudflat estuaries on the southern and south-eastern shore (Fig. 1). Of these the Motueka River is by far the largest, with a mean annual flow of c. $2.8 \times 10^9$ m$^3$ year$^{-1}$ compared with $1.27 \times 10^9$ m$^3$ year$^{-1}$ for the other three rivers combined (Fig. 2A). Daily mean flow data for the major tributaries of Tasman Bay were provided by the Tasman District Council (Fig. 2, Table 1). The total discharge for each river was calculated by increasing the gauged discharge proportionate to the area of the catchment not gauged because, for all these rivers, the gauging stations are situated some distance from where the rivers enter the sea. Historical inorganic nutrient data collected from some of the Tasman Bay rivers were obtained from published (Close & Davies-Colley 1990a,b; Biggs & Gerbeaux 1993) and unpublished data (Biggs pers. comm.) supplemented with data collected during a flood cycle in the Motueka River (sampled at the State Highway 60 bridge) between 1 and 8 October 1996. The inorganic nitrogen loads entering the bay in 1995 and 1996 were calculated using mean concentrations for low (<10 m$^3$ s$^{-1}$), medium (10–100 m$^3$ s$^{-1}$), and high (>100 m$^3$ s$^{-1}$) flow conditions.

**RESULTS**

**Freshwater nutrient inputs**

The pervasive influence of the low salinity river plumes throughout the study area were apparent in the molar ratios of the inorganic macronutrients in the sea water (Table 2, Fig. 3). DIN:DRP ratios were always higher in surface waters than at depth, because of the relative enrichment of DIN over DRP in freshwater inflows. Conversely, DIN:DRSi ratios were lower in surface sea water throughout the bay because of the relative enrichment with DRSi in fresh waters. Inorganic nitrogen, silica, and phosphorus ratios in the Motueka River are typical of those observed in pristine river environments (e.g., the Mackenzie and Yukon Rivers) compared with those in major river systems (e.g., the Seine and Rhine Rivers) that are heavily impacted by anthropogenic inputs (Table 2).

The inorganic nutrient loads carried by the main freshwater tributaries that discharge into Tasman Bay were calculated from historical data (Fig. 4) and data from the analysis of Motueka River waters at intervals over two flood cycles between 1 and 8 October 1996 (Fig. 5). The assumption was made that the nutrient concentrations in the smaller rivers were the same as those in the Motueka River. Concentrations of nitrate-N and DRSi were lowest under extreme low and extreme high flow conditions whereas ammonium-N and DRP concentrations

### Table 2  
Dissolved inorganic nitrogen (DIN), dissolved reactive silica (DRSi), and dissolved reactive phosphorus (DRP) molar ratios.

<table>
<thead>
<tr>
<th>Location and date</th>
<th>DIN:DRP</th>
<th>DIN:DRSi</th>
<th>DRSi:DRP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 m</td>
<td>All depths except 0 m</td>
<td>0 m</td>
</tr>
<tr>
<td><strong>Sea waters</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tasman Bay, 15–16 May 1996</td>
<td>7.40</td>
<td>5.64</td>
<td>0.21</td>
</tr>
<tr>
<td>Tasman Bay, 19–20 Jul 1996</td>
<td>13.51</td>
<td>7.28</td>
<td>0.29</td>
</tr>
<tr>
<td>Tasman Bay, 28–29 Aug 1996</td>
<td>4.52</td>
<td>3.73</td>
<td>0.09</td>
</tr>
<tr>
<td>Tasman Bay, 9–10 Oct 1996</td>
<td>8.77</td>
<td>4.59</td>
<td>0.26</td>
</tr>
<tr>
<td><strong>River waters</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Motueka River, 1–8 Oct 1996</td>
<td>38.23</td>
<td>–</td>
<td>0.07</td>
</tr>
<tr>
<td>MacKenzie (Canada)*</td>
<td>37.5</td>
<td>–</td>
<td>0.05</td>
</tr>
<tr>
<td>Yukon (Alaska)*</td>
<td>23.9</td>
<td>–</td>
<td>0.03</td>
</tr>
<tr>
<td>Rhine (Germany)*</td>
<td>22.1</td>
<td>–</td>
<td>2.5</td>
</tr>
<tr>
<td>Seine (France)*</td>
<td>18.6</td>
<td>–</td>
<td>3.5</td>
</tr>
<tr>
<td>Mississippi (United States)*</td>
<td>15.0</td>
<td>–</td>
<td>1.1</td>
</tr>
</tbody>
</table>

*After Justic et al. (1995).
were less predictably related to flow. To calculate the total nitrogen load, low flow (<10 m$^3$ s$^{-1}$), medium flow (10–100 m$^3$ s$^{-1}$), and high flow (>100 m$^3$ s$^{-1}$) total dissolved inorganic nitrogen concentrations of 3.4, 11.1, and 5.4 mmol-N m$^{-3}$ respectively were applied (derived from data in Fig. 4) to 1995 and 1996 total daily discharges of each of the four major Tasman Bay rivers (Table 3). To calculate DRP and DRSi loads, mean values of 9.8 mg P m$^{-3}$ and 3.5 g Si m$^{-3}$ respectively were used. 1996 was a relatively dry year and the nutrient loads were c. 26% less than in 1995. Approximations of the total DIN discharge were 513.8 and 379.2 t N in 1995 and 1996 respectively (Table 3). Total DRP and DRSi discharges were 45.4 and 34.6 t P and 1.6 $\times$ $10^4$ and 1.2 $\times$ $10^4$ t Si in 1995 and 1996 respectively.

**Inorganic nitrogen in sea water**

Long-term monitoring of dissolved inorganic nitrogen concentrations (Fig. 6) revealed consistent seasonal patterns of high nitrate and nitrite concentrations during late autumn and winter (May–August). These were usually the highest mean water
column concentrations within each year. However, in some years during late spring and early summer (e.g., November 1992), spikes or prolonged periods (e.g., February – April 1993 and September – December 1993) of high nitrate concentrations, in the complete absence or presence of only low levels of nitrite, were also observed. These periods were usually characterised by an increase in nitrate at all depths sampled in the water column with salinity’s >34. On some occasions (e.g., November 1992), high surface concentrations associated with low salinity (<33) waters indicated that nitrate-enriched river plumes had spread onto the sampling sites. Except for midwinter periods coincident with the nitrate maximum, nitrite was usually undetectable in surface and mid water column (10 m) waters for most of the year, though trace levels could often be detected in near bottom waters. It was these higher concentrations in deeper waters that were responsible for the traces of nitrite appearing during some summer periods (e.g., January–March 1992). Unusually, on one occasion in midsummer (February 1993; Fig. 6), detectable nitrite (>0.1 mmol-N m⁻³) was observed at all depths, including the surface.

Weekly observations at sites 7B and 4B during the spring of 1996, show the spatial and temporal variability that can be expected in inorganic nutrient and phytoplankton biomass measurements over smaller time and space intervals (Fig. 7). The bloom during the 1996 spring (Fig. 7A) did not achieve a high biomass (max. Chl. a 1.5 µg litre⁻¹) and this resulted in a slow decline in nitrate-N (Fig. 7B) within the water column, though all nitrite-N had disappeared by mid September. DRP concentrations changed little and remained relatively high throughout this period (Fig. 7A). Ammonium-N concentrations (Fig. 7C) were usually quite similar at the two sites but on some occasions differed substantially. For example, the wide error bars in mid July result from very high levels of ammonium-N.

Table 3  Dissolved inorganic nitrogen (DIN), phosphorus (DRP), and silica (DRSi) loads (t/year) discharged into Tasman Bay, New Zealand, in 1995 and 1996.

<table>
<thead>
<tr>
<th></th>
<th>Total DIN load</th>
<th>Total DRP load</th>
<th>Total DRSi load</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(t N/year)</td>
<td>(t P/year)</td>
<td>(t × 10³ Si/year)</td>
</tr>
<tr>
<td>Maitai River</td>
<td>23.4</td>
<td>13.0</td>
<td>2.4</td>
</tr>
<tr>
<td>Waimea River</td>
<td>131.3</td>
<td>75.9</td>
<td>11.2</td>
</tr>
<tr>
<td>Motueka River</td>
<td>334.2</td>
<td>290.3</td>
<td>29.6</td>
</tr>
<tr>
<td>Riwaka River</td>
<td>24.8</td>
<td>16.2</td>
<td>2.3</td>
</tr>
<tr>
<td>Total</td>
<td>513.8</td>
<td>379.2</td>
<td>45.5</td>
</tr>
</tbody>
</table>
(1.6 mmol m\(^{-3}\)) throughout the water column at site 7B, and its complete absence at site 4B. The peaks in DRSi (Fig. 7D) coincided with plumes of lower salinity DRSi-enriched water moving onto these sites and elevating the concentrations in surface waters.

Major flood events within the Tasman Bay catchment greatly affected the salinity of surface waters throughout the bay, and outwelling plumes of low salinity water issuing from the Motueka River mouth and the southern estuaries frequently extended beyond the confines of the study area (Fig. 8A). The most widespread low salinities (<32) were observed on 3 October 1995, after the large flood peaks in late September (Fig. 2B). Under all flow regimes the discharge from the Motueka River resulted in the western side of the bay always having lower surface salinities than the eastern side. During most surveys, on occasions immediately following major floods (3 October 1995, 19–20 July 1996), and during periods of low flows in the Motueka River, the freshwater plume exited the study area northwards along the north-west coast. On these occasions outwelling plumes from the Maitai and Waimea Rivers also displayed a north-westward orientation along the western shore as higher salinity surface waters intruded southward along the eastern shore.

The spatial distribution of nitrate-N in surface waters of the bay was, on most occasions, directly related to its introduction in the river plumes (Fig. 8E–H). Following major floods within the catchment (Fig. 8; 3 October 1995, 19–20 July 1996)
concentrations of nitrate-N over large areas of the bay were substantially elevated. On all sampling occasions, the influence of the outwelling plumes from estuaries and river mouths was observable in the elevated nitrate-N concentrations along the southern and western shores. During the midwinter nitrate maximum (e.g., 19 July 1996) the elevated nitrate concentrations in the outwelling plumes was still apparent, superimposed on the moderately high concentrations of nitrate that existed in higher salinity offshore waters. Even in otherwise nutrient depleted surface waters during midsummer periods (e.g., 22 February 1996), moderate levels of nitrate-N were observed associated with salinity fronts and in isolated parcels of low salinity water apparently shed some time before off the outwelling plumes.

The vertical distribution of salinity and nitrate-N within depth profiles along transect 7 (Fig. 1) showed that in this region the influence of the Motueka River plume was pervasive in terms of its effect on salinity

![Fig. 7 Combined water column mean concentrations of seawater properties at sites 4B and 7B, July–December 1996. A, Chlorophyll a (Chl. a) and dissolved reactive phosphorus (DRP); B, nitrate-N and nitrite-N; C, ammonium-N; D, dissolved reactive silicate DRSi.](image-url)
Fig. 8  (and overleaf) Plots of surface seawater properties during selected seasonal survey periods (Spring, 3 October 1995 and 3 November 1995; Summer, 22 February 1996; Winter, 19 July 1996). A–D, Surface salinity; E–H, surface nitrate-N (mmol-N m⁻³); (see overleaf) I–L, surface dissolved reactive phosphorus (DRP, mmol-P m⁻³); M–P, surface dissolved reactive silicate (DRSi, mmol-Si m⁻³). A and I show the location of sampling sites.
Fig. 8 continued
Fig. 9 Water column profiles of salinity on transect 7 off the mouth of the Motueka River, New Zealand, during selected synoptic surveys.
Fig. 10  Water column profiles of nitrate-N (mmol-N m⁻³) along transect 7 off the mouth of the Motueka River, New Zealand, during selected synoptic surveys.
MacKenzie—River inputs, re-mineralisation

Fig. 11  Water column profiles of nitrite-N (mmol-N m⁻³) on transect 7 off the mouth of the Motueka River, New Zealand, during selected synoptic surveys.
Fig. 12  Plots of the sea-surface distribution and water column profiles of ammonium -N (mmol-N m⁻³) concentrations on two successive synoptic survey occasions (19–20 July 1996 and 28–29 August 1996).
(Fig. 9) and nitrate-N distribution (Fig. 10) in surface and near surface waters, although its direct influence rarely extended deeper than 5 m. On most sampling occasions in waters beyond and below the low salinity plume, nitrate-N was undetectable except during the early and midwinter surveys (15–16 May 1996, 19–20 July 1996) when high concentrations of nitrate-N, representative of the annual nitrate maxima, existed throughout the water column.

Changes in the vertical distribution of nitrate-N and nitrite-N within the water column on Transect 7 (Fig. 11) also followed seasonal patterns. During midsummer (January–February) nitrite-N was only detectable in near bottom waters at the deepest
stations. As the seasons progressed through autumn and winter (March–July) concentrations increased and the near bottom nitricline advanced into shallower depths. By mid July nitrite was detectable throughout the entire water column. By late winter (28–29 August 1996) and spring (9–10 October 1996) the nitricline again descended and became only detectable in near bottom waters >25 m deep. Changes in the vertical distribution of nitrate-N were similar though it was usually at rather high levels within surface waters directly affected by the Motueka plume. The spatial and temporal distribution of ammonium in surface waters and within water column profiles closely resembled that of the nitrate-N distributions though the concentration gradients tended to be more extreme. The highest concentrations were generally observed near shore along the south and west coasts (Fig. 12A) extending into the bay in association with the freshwater plumes (Fig. 8). An ammonium maximum (Fig. 12C) occurred in synchrony with the midwinter water column nitrite-N and nitrate-N maxima and on 28–29 August higher surface ammonium concentrations were observed in higher salinity offshore waters on the margins of the study area (Fig. 12D).

**Inorganic silicates in sea water**

Very high dissolved reactive silica concentrations (max. 170 mmol Si m⁻³) were associated with low salinity coastal waters. Major flood events resulted in elevated concentrations throughout the bay as a whole and permanent concentration gradients persisted in near-shore waters along the south and west coasts (Fig. 8M–P). There was a strong inverse relationship between DRSi and salinity in surface waters (Fig. 3). Data from transect 7 (Fig. 13) illustrate the impact of the Motueka River plume on surface and near surface silica concentrations. The low dissolved reactive silica concentrations observed in the mid–upper water column during the May survey (Fig. 13), and the persistence of low, deep water concentrations during the winter (July and August), is suggestive of silicate draw-down because of an autumnal diatom dominated phytoplankton bloom that occurred at this time.

**Inorganic phosphorus in sea water**

Concentration gradients of dissolved reactive phosphorus were the least predictable and explicable of all the dissolved inorganic nutrient parameters. Although inshore-offshore gradients existed (Fig. 8I–L), their magnitude was frequently not large and only rarely was this element at levels below the limits of analytical detection in surface or subsurface waters. There was no relationship between salinity and DRP (Fig. 3B) in surface waters and major flood events did not induce the same bay-wide changes in surface concentration as for the nitrogen and silica species. There was however, a seasonal DRP maximum in July (Fig. 8L) at the same time as the midwinter maxima of other inorganic nutrients. The surface water distribution of DRP in the low salinity plumes from the rivers and estuaries suggested DRP behaved differently in waters from the different sources. Higher concentrations were almost always found within the plumes of the Nelson Haven, Waimea, and Moutere Inlets. In contrast, DRP concentrations within the highly turbid plume of the Motueka River were usually low. A mid-bay northwest/south-east orientated surface water concentration maximum approximately aligned along the 15 m depth contour as shown for 19 July 1996 (Fig. 8L) was observed on 6 of the 11 sampling surveys.

**DISCUSSION**

The nutrient concentrations measured in Tasman Bay waters during these surveys, though brief snapshots in time, extend previous research and monitoring at a few sites. They represent the net effect of transport of these nutrients into and out of the bay in rivers and currents, and assimilation, storage, and regeneration processes in the water column and sediments. They provide a picture of the effect of episodic flood events superimposed on underlying seasonal hydrographic and biogeochemical processes, and provide a perspective on the relative importance of some of the various sources of inorganic nutrients that drive the productivity of the system. These data provide a starting point for the formulation and validation of hydrodynamic and ecosystem function models of Tasman Bay and adjoining regions.

The annual appearance of nitrite-N in the <30 m deep water column of Tasman Bay is the single most predictable seasonal water chemistry marker and is clearly linked to the annual nitrate maxima. Nitrite-N is undetectable during most of the year throughout the water column except for trace amounts in deeper (>30 m) waters. In April–May, concentrations begin to increase in deep near bottom waters and this increase progressively spreads into shallower areas until by midwinter nitrite is present (0.1–0.6 mmol NO₂⁻-N m⁻³) throughout the water column, over the entire bay. Nitrate-N concentrations follow a similar
but somewhat less predictable pattern. Throughout the water column for much of the year, nitrate-N is undetectable except in deeper waters at the bottom of the euphotic zone though it is always detectable in near-shore surface waters associated with the freshwater plumes. Nitrite-N is undetectable under all flow regimes in freshwater inputs at all times of the year and the water column nitrite-N maximum is obviously generated in situ.

The development of the nitrate/nitrite maximum may arise from changes in the relative rates of assimilation and regeneration because of the suppression of phytoplankton photosynthesis and nutrient assimilation as a result of seasonal light limitation. In this instance the rates of (light-independent) nitrogen re-mineralisation and transformation within the water column and sediments become dominant processes and a net accumulation of inorganic nutrients takes place. Biological processes which lead to the appearance of nitrite-N in the coastal water column are denitrification, including assimilatory and dissimilatory nitrate reduction (Hattori 1983), and nitrification by ammonium oxidation (Kaplan 1983). Nitrite-N accumulation occurs when the rate of one or other of these processes exceeds the capacity of algae or bacteria to assimilate it (Kamykowski & Zentara 1991). It has been shown using tracer methods (Ward et al. 1989), that the production of nitrate-N in the water column can be detected even when nitrate-N concentrations are declining because of phytoplankton assimilation. There is strong support for the notion that nitrification is the dominant process in determining the profiles of nitrite-N in coastal and offshore waters (Holligan et al. 1984). The potential importance of bacterial nitrification in supplying regenerated nitrate-N to the phytoplankton with the euphotic zone has been demonstrated, in New Zealand waters, by Priscu & Downes (1985). By the measurement of nitrogen uptake rates, ammonium oxidation rates, and nitrous oxide levels in western Cook Strait (offshore of Tasman Bay), they estimated that ammonium oxidation by nitrifying bacteria accounted for c. 30% of the total ammonium utilisation (i.e., bacterial and algal) and may supply c. 40% of the phytoplankton nitrate-N requirements.

Estimates of the nitrification rate in a New Zealand upwelling region (Viner 1990) using the dark $^{14}$C uptake method, ranged from c. 7% to 12% of the total N and ammonium uptake respectively. Likewise, Dore & Karl (1996) demonstrated in tropical oceanic waters that nitrification in the euphotic zone is an important source of regenerated nitrate-N. They estimated that nitrate regeneration by nitrification may be 47–142% of the concurrent nitrate-N assimilation rate within the euphotic zone. During the summer, when the water column above the pycnocline is largely depleted of nutrients, nitrification is still taking place but the precursors (ammonium) and products (nitrite and nitrate) are being turned over so quickly that they do not accumulate except in deeper water below the euphotic zone. In Tasman Bay, data presented here suggests that the close dynamic relationship between nitrification and nitrogen assimilation occasionally becomes uncoupled because of transient slow downs in assimilation rate because of limitation by other essential elements, the most likely of which is phosphorus. It is believed that this may be the reason for the peaks in nitrate-N that occasionally appear (e.g., December 1993) during summer in Tasman Bay waters (Fig. 6). One of the causes of this may be the sporadic appearance of phytoplankton species that produce copious quantities of mucilage that has a high affinity for phosphorus. MacKenzie et al. (2002) identified midsummer blooms of the dinoflagellate Gonyaulax hyalina as having just such an effect. The hypothesis is that the massive quantities of mucilage produced by this species results in the water column being stripped of inorganic phosphorus, which is deposited on the sediments, with a consequential rise in the levels of nitrate-N as the phytoplankton becomes limited by phosphorus and DIN assimilation rates decline.

The inorganic nutrient concentrations in the surface sea-waters of Tasman Bay are significantly affected by freshwater run-off from extensively modified catchments. However, the actual concentrations are very much lower than those encountered in similar locations elsewhere that are subject to high levels of agricultural, industrial, and urban pollution. In San Francisco Bay, California for example (Cloern 1996), typical winter levels of nitrate-N, ammonium-N, DRSi, and DRP are 40–80, 10–15, 70–130, and 5–10 mmol m$^{-3}$ respectively. For all but silica, these concentrations are up to an order of magnitude above the maximum levels observed in Tasman Bay.

Except in surface waters during midwinter flood events (e.g., July 1996; Table 2) inorganic N:P and N:Si ratios (4.6–8.8 and 0.09–0.29 respectively) were significantly below the optimum Redfield ratios (16:1 and 1:1 respectively) for phytoplankton growth. Conversely, N:P ratios in the Motueka River waters were high and the inorganic nitrogen content observed in the surface waters reflect the net effect.
of mixing of sea and river waters and phytoplankton assimilation. These ratios imply that inorganic nitrogen is the element most limiting production in the region, though as Geider & Roche (2002) have emphasised, the Redfield ratio does not reflect a fundamental constraint on the elemental composition of primary production. They suggest that the critical N:P ratio that marks a transition between N and P limitation is significantly higher than the Redfield ratio (maybe 20–50 molN: molP). In various river-plume dominated coastal regions throughout the world (e.g., Northern Adriatic Sea, North Sea, Northern Gulf of Mexico), there is concern that changes in stoichiometric nutrient ratios may be associated with coastal eutrophication (Justic et al. 1995, 2003; Lohrenz et al. 1997). In river systems heavily impacted by agriculture and urban effluents, increases in N and P concentrations relative to Si concentrations result in the potential for the development of Si limitation in coastal receiving waters. This decreases the potential for N and P limitation which in extreme examples may result in benthic hypoxia, selection for problematic flagellate species, and reduction in the role of diatoms in productivity. Although there are anecdotal accounts that suggest benthic deoxygenation events have occurred in the historical past (cited in MacKenzie et al. 2002) there are no real grounds for concern on this score for the Motueka River and the coastal waters of Tasman Bay (Table 2). The observed nutrient ratios are very different from highly enriched rivers flowing from intensively exploited catchments (e.g., the Rhine, Seine, and Mississippi) and are more typical of those of pristine rivers with largely uninhabited catchments (e.g., the Mackenzie and Yukon).

One objective of this study was to obtain data that would provide a perspective on the significance of freshwater nutrient inputs relative to enrichment from other sources to Tasman Bay sea waters. Unfortunately it is not possible at this stage to estimate the contribution that oceanic advection makes to nutrient enrichment of the Tasman Bay coastal zone although the completion and validation of the hydrodynamic model (Tuckey et al. 2003) will considerably assist in providing this information in the future. The residual circulations produced by this model have so far been somewhat different from the widely accepted circulation for the Bays described by Heath (1969) of a counter clockwise flow of water around Tasman Bay. Model simulations (Tuckey pers. comm.) have shown a strong residual northwest flow along the western shoreline of the bay that is consistent with the observations of the progression of salinity and nutrient distributions made here. In enclosed waters such as the Rhode River estuary (Jordan et al. 1991), long-term (>18 year) monitoring has shown that the magnitudes of seasonal changes in phytoplankton biomass are correlated with the magnitude of river flows of the previous spring. This together with seasonal changes in inorganic N:P ratios leads to the hypothesis that in spring Chl. a concentrations are controlled by riverine nitrate-N inputs, whereas in summer they are controlled by the regeneration of inorganic N from organic matter produced in the spring. So far there are insufficient data to substantiate this hypothesis in Tasman Bay, and since it is an open system from which much of the freshwater inflow may be advected without having a major stimulating effect on the phytoplankton, cause and effect may be somewhat less direct.

The rather stable concentrations of DRP in Tasman Bay sea waters suggest this element is rarely a factor limiting phytoplankton production although there are some features of its spatial distribution that are interesting. It is probable that the relatively high suspended sediment loads in Tasman Bay waters may play an important role in regulating the availability of reactive phosphorus to phytoplankton. The anomalously low concentrations of DRP measured in the turbid Motueka River plume are consistent with adsorption of phosphorus to suspended clay particles, and the mid bay DRP maximum that was frequently observed in surface waters suggests that desorption of DRP may take place at offshore salinity fronts (Viner 1982).

It has been suggested that in some heavily populated/urbanised areas, atmospheric nitrogen deposition to adjacent coastal seas, originating from fossil fuel combustion and atmospheric emissions from intensive agriculture, may be significant to the nitrogen budget in these waters (Paerl et al. 1990). In this context inputs of up to 16.6 mmol-N m⁻² month⁻¹ (70 000 t / 24 500 km² per year) equivalent to c. 30% total N input load (at times exceeding the riverine input) have been estimated for the German Bight of the North Sea (Bedding et al. 1997). Combined nitrate and ammonium concentrations (78% ammonium-N) in rainwater collected within Nelson City and on adjacent rural land have varied from undetectable to 2.6 mmol-N m⁻³ (MacKenzie unpubl. data). Given an average rainfall in Nelson of 975 mm year⁻¹, the maximum average quantity of atmospheric nitrogen deposition on the Tasman Bay study area could be as much as 66 kg-N/day or
c. 18% of the river input. This estimate should however be treated with extreme caution as only a very limited number of rainwater analyses have been carried out and the potential for sample contamination during collection and small analytical errors may have a very large effect on estimations of this value.

Seasonal variations in the influx and efflux of DIN from the sediments of Tasman Bay probably play an important role in the observed seasonal changes in nutrient concentrations in the water column. For much of the year, and over most of the study area, the euphotic zone encompasses the entire water column and the waxing and waning of its influence on nutrient flux across the sediment/water interface may be an important regulator of the development of the annual nitrate/nitrite maximum. The net effect of sediment nutrient re-mineralisation could be observed in turbid near-shore locations (5–10 m) within the water column profiles off the Motueka River mouth (Fig. 10, 11), where near bottom DIN concentrations were often significantly elevated. Gibbs et al. (2002) have calculated that up to 80% of the annual DIN supply for Beatrix Bay (a large embayment within the Marlborough Sounds, New Zealand) may come from sediment recycling. However, as they point out, during strongly stratified periods much of this DIN may not be accessible to phytoplankton within the upper water column. Christensen et al. (2003) have shown that at one 20–24-m-deep site (T3) in Tasman Bay (site 7B in this study), the rates of O₂, nitrate-N and ammonium-N flux, and the rate of denitrification are highly dependent on ambient light conditions and the metabolic activity of the benthic micro-algae community. Using the data of Christensen et al. (2003) a comparison has been made of the bulk quantities of inorganic nitrogen in the Tasman Bay water column during nutrient depleted (January–February) and nutrient replete (May–July) periods (Table 4) with potential inorganic nitrogen sources (rivers, sediment efflux) and sinks (de-nitrification). Although these are approximations, and only provide a brief glimpse of the net effects of highly dynamic biogeochemical processes, they raise questions as to the relative significance of the river inputs. On average, the amount of inorganic nitrogen entering the study area in the river waters is less than half of the amount of nitrate-N and ammonium-N released by the sediments and contributes only c. 20% of the amount of nitrogen lost from the sediments through de-nitrification. Direct estimates and biogeochemical modelling studies on similar ecosystems elsewhere

<table>
<thead>
<tr>
<th>Depth range (m)</th>
<th>Area (km²)</th>
<th>NO₃⁻ + NO₂⁻ (t N)</th>
<th>Sediment efflux</th>
<th>Sediment denitrification</th>
<th>Mean influx (1995–96)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20–30 m</td>
<td>225.2</td>
<td>25.3</td>
<td>34.8</td>
<td>190.4</td>
<td>260.5</td>
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<tr>
<td>10–20 m</td>
<td>202.4</td>
<td>11.5</td>
<td>31.4</td>
<td>190.4</td>
<td>80.2</td>
</tr>
<tr>
<td>5–10 m</td>
<td>95.7</td>
<td>7.2</td>
<td>8.3</td>
<td>13.8</td>
<td>37.0</td>
</tr>
<tr>
<td>&lt;5 m</td>
<td>62.4</td>
<td>1.8</td>
<td>3.1</td>
<td>3.9</td>
<td>3.9</td>
</tr>
<tr>
<td>Total</td>
<td>633.7</td>
<td>45.8</td>
<td>77.6</td>
<td>134.9</td>
<td>533.1</td>
</tr>
</tbody>
</table>

*Calculated from values in Christensen et al. (2003).*
(e.g., the North Sea), suggest that de-nitrification in the sediments of coastal/shelf seas are significant, global scale, sinks of combined nitrogen (Hydes et al. 1999). Clearly, to provide the bulk of the inorganic nitrogen that contributes to the winter nitrate/nitrite maximum (e.g., 533 t N in July 1996) in Tasman Bay, other sources such as water column nitrification and advection of offshore nitrate/nitrite enriched waters into the bay must play a major role. This is not to suggest that the influence of the river inflows on productivity within the bay is unimportant. There are many other attributes of the freshwater inflows, such as the effect on water column stratification, the high suspended sediment loads, and the contribution of other essential elements (e.g., Fe and Si), that are important regulators of phytoplankton production.

CONCLUSION

A synopsis of spatial and temporal changes in the distribution of inorganic nutrients over an annual cycle in near-shore Tasman Bay has been presented. Flood events in the bay’s catchment cause substantial changes in the distribution of salinity and levels of dissolved inorganic nitrogen, phosphorus, and silica in surface waters, however the magnitude of this nutrient enrichment in comparison to other potential sources is debatable. Estimates of the amount of inorganic nitrogen entering the study area in the river inputs is less than half the amount of nitrate and ammonium-N released by the sediments and in the order of only 20% of the amount of combined nitrogen lost from the sediments through denitrification. To provide the bulk of the inorganic nitrogen that contributes to the winter nitrate/nitrite maximum, other sources such as water column nitrification and advection of offshore nitrate/nitrite enriched waters into the bay must play a major role. Unfortunately at the present time there are not sufficient data available to be able to make an educated guess at the actual magnitude of nutrient enrichment from offshore and this will depend on new field observations and further development of circulation models of the bay. Further work on the development of a freshwater nutrient inflow model to more accurately calculate nutrient loads is needed. Direct estimates of the rates of nutrient fluxes (assimilation and re-mineralisation) within the water column and sediments would also assist in the construction of realistic nutrient budgets and productivity models for this region.

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