Cawthron Report No. 837



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



Prepared for

Stakeholders of the Motueka Integrated Catchment Management Programme







July 2003



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

# Motueka Integrated Catchment Management (Motueka ICM) Programme Report Series

by

# Lincoln MacKenzie, Paul Gillespie and Stephanie Thompson

Cawthron Institute 98 Halifax Street East Private Bag 2 NELSON NEW ZEALAND Phone: +64.3.548.2319 Fax: +64.3.546.9464 Email: info@cawthron.org.nz

Information contained in this report may not be used without the prior consent of the client Cover Photo: Satellite image of Tasman Bay from the Terra satellite using MODIS sensor, 30 May 2002 (courtesy of NASA's Visible Earth directory).



# PREFACE

An ongoing report series, covering coastal-sea components of the Motueka Integrated Catchment Management (ICM) Programme, has been initiated in order to present preliminary research findings directly to key stakeholders. The intention is that the data, with brief interpretation, can be used by coastal managers, environmental groups and users of coastal marine resources to address specific questions that may require urgent attention or may fall outside the scope of ICM research objectives. We anticipate that providing access to marine environmental data will foster a collaborative problem-solving approach through the sharing of both ICM and privately collected information. Where appropriate, the information will also be presented to stakeholders through follow-up meetings designed to encourage feedback, discussion and coordination of research objectives.



# TABLE OF CONTENTS

1	INTRODUCTION1								
2	METHODS	2							
2.1	Sampling2	2							
2.2	Nutrient analyses4	ł							
3	RESULTS								
3.1	Seawater nutrients								
	3.1.1 Inorganic nitrogen	<del>,</del>							
	3.1.2 Inorganic silicates	7							
	3.1.3 Inorganic phosphorus	7							
4	DISCUSSION	3							
4.1	Inorganic nitrogen	3							
	4.1.1 Atmospheric nitrogen deposition	)							
	4.1.2 Sediment nitrogen recycling and denitrification	)							
4.2	Inorganic silicates	<u>)</u>							
4.3	Freshwater nutrient inflow12	2							
5	SUMMARY14	ŀ							
5.1	Background14	ł							
5.2	Study objective	ł							
5.3	Nutrient dynamics14	ł							
6	ACKNOWLEDGEMENTS15	5							
7	REFERENCES	5							

# LIST OF TABLES

Table 1. Timing of sampling surveys relative to recent Motueka River flows	4
Table 2. Inorganic nitrogen, silica and phosphorus molar ratios	7
Table 3. Dissolved inorganic nutrient loads discharged into Tasman Bay in 1995 and 1996	7
Table 4. Bulk quantities of nitrate-N and nitrite-N in the water column of the Tasman Bay stu	ıdy
area (<30m) during summer (Jan & Feb 1996) and autumn/winter periods (May & July 1996)	6),
relative to approximations of DIN influx from the rivers, and sediment efflux a	and
denitrification	.14

# **LIST OF FIGURES**

Figure 1. Geographic location of Tasman Bay and major fresh water inputs, bathymetry (1A) and
location of sample survey sites and transects (1B)
Figure 2. The relative magnitude (m <sup>3</sup> $\times 10^9$ / year) of the total annual discharge (2A) during 1995
and 1996 and combined total daily flows ( $m^3 \times 10^6$ /day) in the Motueka, Riwaka, Waimea and
Maitai rivers during the sampling survey period (2B)
Figure 3. Average combined depth weighted mean nitrate-N and nitrite-N concentrations (mmol-N
m <sup>-</sup> ) at sites B1, B2 and B7, 1991-199620
Figure 4. Combined depth weighted mean concentrations of water column properties at sites B4 and
B7 Jul-Dec 1996. Chla and DRP (4A); Nitrate-N and Nitrite-N (4B); Ammonium-N (4C);
DRS1 (4D)
Figure 5. Plots of surface seawater properties during selected seasonal survey periods. 5A, surface
salinity (psu); 5B, surface nitrate-N (mmol-N m <sup>3</sup> ); 5C, surface DRP (mmol-P m <sup>3</sup> ); 5D,
surface DRS1 (mmol-S1 m <sup>-3</sup> )
Figure 6. Water column profiles of salinity (psu) on Transect 7 off the mouth of the Motueka River,
during selected synoptic surveys
Figure 7. Water column profiles of nitrate-N (mmol m <sup>-3</sup> -N) along transect 7 off the mouth of the
Motueka River during selected synoptic surveys
Figure 8. Water column profiles of nitrite-N (mmol-N m <sup>-3</sup> ) on transect 7 off the mouth of the
Motueka river during selected synoptic surveys
Figure 9. Water column profiles of DRSi (mmol-Si m <sup>-3</sup> ) on transect 7 off the mouth of the Motueka
river during selected synoptic surveys
Figure 10. Plots of the sea-surface distribution and water column profiles of ammonium -N (mmol-
N m <sup>-3</sup> ) concentrations on two successive synoptic survey occasions
Figure 11. Salinity and inorganic nutrient concentrations in surface waters for all data collected
during synpotic surveys Each plot represents 441 individual data points. 5A: Nitrate-N, 5B:
Dissolved reactive phosphorus, 5C: Dissolved reactive silica
Figure 12. DIN concentrations versus flow in the Motueka River, data from Biggs and Gerbeaux
(1993), Close and Davis Collie (1990) and analyses over two flood cycles in the Motueka
River 1-8 October 1996
Figure 13. Inorganic nutrient concentrations over two flood cycles in the Motueka River, 1-8
October 1996

Report reviewed and approved for release by:

Dr Barry Robertson Manager Coastal & Estuarine Group

# **1 INTRODUCTION**

The information provided in this report has been collated and interpreted as part of a collaborative research effort called the Motueka Integrated Catchment Management (ICM) programme. Refer to Basher (2003) for a description of the programme structure and rationale. The programme was designed to assess the effects of various land use practices on terrestrial, freshwater and marine ecosystems in a *"ridge top to the sea"* approach. As part of a Cawthron Institute (Cawthron) investigation into the effects of freshwater inflow quantity and quality on the productivity of the marine receiving environment, a series of detailed spatial surveys of the nutrient structure of the water column in Tasman Bay were reviewed. Key external nutrient sources and internal recycling processes were compared in order to evaluate their relative importance to the fertility and productivity of the coastal ecosystem.

The waters and sea-floor of Tasman Bay (Figure 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  $(3876 \text{ km}^2)$  watershed of the Bay are extensive horticultural, forestry and pastoral industries. The Bay receives water from several significant rivers, the largest of which is the Mouteka River with a catchment of 2180 km<sup>2</sup> (Basher 2003). There are two main urban centres (total population  $\approx 60,000$ ) which discharge treated sewage, untreated stormwater and light industrial effluent. All these activities may conflict with the maintenance of a high standard of water quality within the Bay which supports important coastal fin-fisheries and shell-fisheries, including a valuable scallop (*Pecten novaezelanidiae*) 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 three large areas offshore of the Motueka River mouth have been designated as an "Aquaculture Management Area" (approximately 4.2 km<sup>2</sup> in total) for future development as a mussel growing region.

Because of the growing body of evidence that human activity is having a significant impact on the nutrient status of shallow coastal seas throughout the world (Jickells 1998, Rabalais *et al.* 2002, Hickel *et al.* 1993, Justic *et al.* 1987), there is an increasing level of international concern about the related intrinsic values of such ecosystems. 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 be having the most important effects. 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, the effects of catchment land-use practices on the nutrient dynamics of Tasman Bay, which is a typical shallow (mean depth 30 m) southern hemisphere embayment, is of particular interest.

There are few published accounts of the water movements within the Bay and most of these were based on extremely limited datasets (Heath 1973; 1976 and Ridgway 1977). These studies identified currents within the Bay as being principally tidally driven although local strong wind events play a major role at times. The mean circulation in Tasman Bay appears to be an anticyclonic gyre although the low-frequency circulation has yet to be adequately investigated. Observational and numerical modelling work, presently being undertaken by Cawthron under the Motueka ICM programme, is investigating these prevailing flows. The results from this work will be reported shortly.



Previously published data on the hydrography, nutrient chemistry, plankton ecology and productivity of the Bay includes a study by MacKenzie and Gillespie (1986) who sampled a single site (12 m depth) at approximately one month intervals over a two-year period between 1982 and 1984. They found that the water column at the sampling site was strongly stratified for most of the year and that the phytoplankton community was typical of a temperate coastal environment with considerable year to year variation in the specific composition and 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. In addition to this study, there has been the sporadic collection of water quality data for various periods of time at monitoring stations coincident with the scallop enhancement zones, and some of these data 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 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 examine the impact of river flow on stratification and nutrient concentrations, as this was thought to be crucial to an understanding of the temporal and spatial variability of biological productivity and the related sustainability of fisheries enhancement. It was recommended that detailed spatial and temporal surveys of the Bay be carried out. The results and interpretation of the surveys carried out as a consequence of this recommendation are recounted here. Results of simultaneous observations on the spatial and temporal distribution of phytoplankton and benthic microalgal biomass relative to water column stratification are reported by MacKenzie *et al.* (in prep) and Gillespie (2003).

## 2 METHODS

## 2.1 Sampling

Synoptic surveys were carried out by sampling 44 stations along five east / west and nine north / south transects across Tasman Bay (Figure 1). The sampling stations were aligned approximately 5 km apart along non-linear transects (A, B, B', C, D) which followed the 30m, 20m, 15m, 10m, and 5m below chart datum contours respectively. Various locations in Tasman Bay experience the highest tidal ranges in New Zealand (up to 5.1 m MHWS) so the actual depth at the time of sampling varied somewhat. Site C3 was in approximately the same location as the main study site (site 2) of MacKenzie and Gillespie (1986). The sampling sites were located to an accuracy of  $\pm$  50 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 within 5-6 hours 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" CTD/fluorometer. At three stations along transect B (1B, 4B, 7B) that were representative of east mid and west Bay areas respectively, water bottle casts were made to obtain samples for dissolved inorganic nutrients analyses, at 5 m intervals from the surface to 1m from the sea-floor. These stations (respectively referred to as sites "Glen", "Ruby Bay" and "Bomber") were the same as those used for long term nutrient and phytoplankton monitoring. At each station along transect 7 (Figure 1B), off the mouth of the Motueka river, water



samples were also collected at the same depths plus an additional sample at 2.5m to include the subsurface plume water.

#### **Definition Box 1: Physical characteristics**

**CTD-** submersible sensor array/data logger that measures conductivity, temperature and depth simultaneously in seawater.

**psu** (or practical salinity units) are based on conductivity and temperature characteristics and are equivalent to parts per thousand (‰). Freshwater would be expected to have a salinity of 0 psu while full seawater would be approximately 35 psu.

**Water column density structure-** The density structure of the water column is controlled by the variation in temperature and concentration of dissolved salts (*i.e.* salinity) with depth. The oceanographic convention is to express density as

 $\sigma_{\text{S.T.P.}}$  (or  $\sigma_{\text{t}}$ ) = (density – 1) x 10<sup>3</sup>).

Thus water with a density of 1.02400 would have a sigma t value of 24.0. Freshwater inflows, because they are less dense than seawater, generally spread out in a floating **plume** of lower salinity (brackish) water over the surface of the sea. When water of lower density is situated above water of greater density, the water column is said to be stable. In other words it is relatively resistant to vertical mixing.

Pycnocline- Depth zones of rapid density change.

Thermocline- Depth zones of rapid temperature change.

Halocline- Depth zones of rapid salinity change.

Eleven surveys were carried out between 3 October 1995 and 9 October 1996. Sampling was undertaken during, and subsequent to, a variety of flow regimes in the Tasman Bay rivers (Figure 2, 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 midwinter and spring 1996, weekly measurements were made of inorganic nutrients and phytoplankton biomass within the water column at the two routine monitoring sites (4B and 7B) in an attempt to capture a more detailed picture of the sequence of events accompanying the development and decline of the spring bloom.

Date	Daily mean river flows (corrected for catchment size) in the Motueka River					
3 October 1995	Coincided with moderate-high river flows (187 m <sup>3</sup> sec <sup>-1</sup> daily mean) and was preceded 3 and 6 days before by two major flood peaks (422 and 452 m <sup>-3</sup> sec <sup>-1</sup> ).					
20 October 1995	Coincided with declining moderate river flows (102 $\text{m}^3 \text{ sec}^{-1}$ ) from a flood peak (416 $\text{m}^{-3} \text{ sec}^{-1}$ ) 5 days before.					
3 November 1995	Coincided with a moderate size flood peak $(131 \text{ m}^3 \text{ sec}^{-1})$ low flow during preceding 14 days.					
22 November 1995	Low flow (38 m <sup>3</sup> sec <sup>-1</sup> ), 11 days since previous moderate flood peak (140 m <sup>3</sup> sec <sup>-1</sup> ).					
9 January 1996	Low flow (27 m <sup>3</sup> sec <sup>-1</sup> ), 10 days after last moderate (166 m <sup>3</sup> sec <sup>-1</sup> ) flood peak and 16 days after last major flood peak (715 m <sup>3</sup> sec <sup>-1</sup> ).					
22 February 1996	Declining low-moderate flow (50 m <sup>3</sup> sec <sup>-1</sup> ), preceded 2 days before by moderate flood peak (190 m <sup>3</sup> sec <sup>-1</sup> ).					
26 March 1996	Declining low-moderate flow (49 m <sup>3</sup> sec <sup>-1</sup> ), preceded 3 days before by moderate flood peak (138 m <sup>3</sup> sec <sup>-1</sup> ).					
15 May 1996	Low flow (26 $\text{m}^3 \text{ sec}^{-1}$ ), 30 days since last moderate-high flood peak (215 $\text{m}^3 \text{ sec}^{-1}$ ).					
19 July 1996	High flow (154 m <sup>3</sup> sec <sup>-1</sup> ), 3 days after major flood peak (409 m <sup>3</sup> sec <sup>-1</sup> ).					
28 August 1996	Moderate flow (80 m <sup>3</sup> sec <sup>-1</sup> ), 7 days after major flood peak (345 m <sup>3</sup> sec <sup>-1</sup> ).					
9 October 1996	Coincided with moderate flood peak (137 m <sup>3</sup> sec <sup>-1</sup> ), one day after maximum flow (237 m <sup>3</sup> sec <sup>-1</sup> ).					

#### Table 1. Timing of sampling surveys relative to recent Motueka River flows

## 2.2 Nutrient analyses

Seawater samples for ammonium (NH<sub>4</sub><sup>+</sup>-N) analysis were frozen (-20°C). Samples for nitrate (NO<sub>3</sub><sup>-</sup>-N), nitrite (NO<sub>2</sub><sup>-</sup>-N), dissolved reactive phosphorus (DRP) and dissolved reactive silicate (DRSi) analyses were preserved with 1 ml/litre of 2% HgCl<sub>2</sub> immediately after collection, filtered (GFC) and refrigerated prior to analysis (Kattner 1999). The phenol-hypochlorite method of Solarzano (1969) was used for the analysis of NH<sub>4</sub><sup>+</sup>-N, NO<sub>3</sub><sup>-</sup>-N and NO<sub>2</sub><sup>-</sup> -N were determined colorimetrically (Strickland and 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 & Si) in mmol m<sup>-3</sup> (=  $\mu$ g atoms 1<sup>-1</sup>) concentrations. All data were plotted using the Golden software "Surfer" three dimensional contouring programme.

Tasman Bay receives freshwater from four main tributaries, 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 (Figure 1). Of these, the Motueka River is by far the largest with mean annual flows of about 2.8  $\times 10^9$  m<sup>3</sup> / year compared to 1.27  $\times 10^9$  m<sup>3</sup> / year for the other three rivers combined (Figure 2A). Additional minor tributaries contribute <0.4  $\times 10^9$  m<sup>3</sup> / year. Daily mean flow data for the major tributaries of Tasman Bay were provided by the Tasman District Council (Figure 2, Table 1). Total flows for each river were calculated by increasing the flow proportionate to the area of the catchment not gauged as, 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 (Biggs and Gerbeaux 1993, Close and Davies-Colley 1990a; 1990b) and unpublished data (Biggs pers comm.) supplemented with some data collected during a flood cycle in the Motueka River (sampled at the



State Highway 60 bridge) between 1st and 8th October 1996. From these, rough estimates of the inorganic nitrogen loads entering the Bay in 1995 and 1996 were calculated using mean concentrations for low ( $<10m^3/sec$ ), medium (10-100 m<sup>3</sup>/sec) and high ( $>100 m^3/sec$ ) flow conditions.

## **Definition Box 2: Nutrients**

**Remineralisation**- decomposition of organic (combined) nutrients to recycle the primary inorganic plant nutrients.

New nutrients- Nutrients entering from outside the system as opposed to those recycled within.

**Dissolved Inorganic Nitrogen** or DIN- the total of ammonium-N, nitrate-N and nitrite-N concentrations.

Eutrophication- the process of nutrient enrichment of aquatic systems.

**Redfield Ratio-** the ratio of macronutrients usually required by phytoplankton (Redfield *et al.* 1963).

**Synoptic nutrient surveys-** nutrient analyses carried out at a number of different locations at or about the same time in order to obtain a spatial overview of conditions.

**Denitrification-** bacteria-mediated process whereby nitrate is reduced to elemental nitrogen, i.e.  $N_2$  gas.

**Nitrification-** bacteria-mediated process whereby ammonium is oxidised to nitrate. Nitrite is an intermediate product.

# **3 RESULTS**

## 3.1 Seawater nutrients

## 3.1.1 Inorganic nitrogen

Long term monitoring of dissolved inorganic nitrogen concentrations within the water column at three sites along the 20 m depth contour (B1, B4, B7) revealed some consistent seasonal patterns (Figure 3). The simultaneous appearance of high nitrate and nitrite concentrations during late autumn and winter (May-August) was the most obvious of these, and usually represented the highest mean water column concentrations within each year. However in some years, during late spring and early summer, high nitrate spikes (*e.g.* Nov. 92) or prolonged periods (*e.g.* Feb. - Apr. 93 and Sept. - Dec. 93) 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 salinities > 34 psu. But on some occasions (*e.g.* Nov. 92) high surface concentrations associated with low salinity (< 33 psu) waters, indicated that nitrate enriched river plumes had spread onto these sampling sites. Except for mid-winter periods coincident with the nitrate maximum, nitrite was usually undetectable in surface and mid profile (10 m) waters for most of the year, though trace levels could often be detected in nearbottom waters. It was these higher concentrations in deeper waters that were responsible for the traces of nitrite appearing during some summer periods (*e.g.* Jan. - Mar. 92). Unusually, on one



occasion in mid summer, (February 1993; Figure 3), detectable nitrite (>0.1 mmol-N m<sup>-3</sup>) was observed at all depths, including the surface.

Weekly observations at sites 7B and 4B, during spring 1996 (Figure 4), show that considerable variability can occur in inorganic nutrient and phytoplankton biomass over relatively small time and space intervals. Usually, however, the measured variables were quite similar at the two sites. The spring 1996 bloom did not achieve a high biomass (maximum chl *a* 1.5  $\mu$ g/l, Figure 4A) and this resulted in a relatively slow decline in nitrate-N (Figure 4B) within the water column, though all nitrite-N had disappeared by mid September. DRP concentrations changed little and remained relatively high throughout the period (Figure 4A). Ammonium-N concentrations (Figure 4C) 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 (1.6 mmol m<sup>-3</sup>) throughout the water column at site 7B, and its complete absence at 4B. The peaks in DRSi (Figure 4D) 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 (Figure 5A). The most widespread low salinities (<32 psu) were observed after the large flood peaks in late September 1995. 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, both on occasions immediately following major floods (3 Oct 95, 19-20 July 96), and during and after 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 the 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 (Figs 5B) though advection, assimilation and regeneration processes clearly had a major impact to the distribution patterns observed over time. Following major floods within the catchment (Figure 5B; 3 October 95, 19-20 July 96) concentrations of nitrate-N were substantially elevated over large areas of the Bay. On all sampling occasions, including periods characterised by low to moderate river flows (3 Nov. 95, 22-23 Feb. 96), 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. Between March 26-27 and July 19-20 1996 the influence of the outwelling plumes was still apparent and, in addition, moderately high concentrations of nitrate were observed in higher salinity offshore waters. During some mid summer periods (9-10 Jan and 22-23 Feb. 1996), moderate levels of nitrate-N were observed in otherwise nutrient-depleted surface waters associated with salinity fronts, and in isolated parcels of low salinity water outside the outwelling plumes. The latter low salinity parcels were apparently shed some time earlier from the plumes, highlighting the hydrodynamic complexity of the system.

The vertical distribution of salinity and nitrate-N within depth profiles along transect 7 (Figure 1) was typical of its distribution throughout the Bay as a whole on each sampling occasion (Figure 6, Figure 7). On transect 7 the influence of the Motueka River plume was pervasive in terms of its effect on salinity (Figure 6) and nitrate-N distributions (Figure 7) in surface and near surface waters. But its direct influence rarely extended deeper than 5 metres and temporal and vertical changes in nitrate concentrations were clearly the result of assimilation and re-mineralisation processes within



the water column and sediments. On most sampling occasions nitrate was undetectable in waters beyond, below, and even in some cases within the low salinity plume. During the early and mid winter surveys (15-16 May 96, 19-20 July 96) high concentrations of nitrate-N, representative of the annual nitrate maxima, existed throughout the water column.

The net result of nitrogen re-mineralisation processes was most clearly demonstrated by changes in the vertical distribution of nitrite-N within the water column on Transect 7 (Figure 8). During mid summer (Jan -Feb.), 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. After this, into late winter (28-29 Aug. 96) and spring (9-10 October 96), the nitricline again descended and became only detectable in near-bottom waters >25m deep. The spatial and temporal distribution of ammonium in surface waters and within water column profiles (Figure 10) closely resembled that of the nitrate distributions though the concentration gradients tended to be more extreme. The highest concentrations were generally observed near shore along the south and west coasts extending into the Bay in association with the freshwater plumes (Figure 10A). An ammonium maximum (Figure 10C) occurred in synchrony with the mid-winter water column nitrite-N and nitrate-N maxima (Figure 7, Figure 8) and on 28-29 August higher surface ammonium concentrations were observed in higher salinity offshore waters on the seaward margins of the study area (Figure 10D).

# 3.1.2 Inorganic silicates

Very high dissolved reactive silica concentrations (maximum: 170 mmol Si m<sup>-3</sup>) were associated with the low salinity coastal waters. Major flood events resulted in elevated concentrations throughout the Bay as a whole and permanent strong concentration gradients persisted in near shore waters along the south and west coasts (Figure 5D). A significant negative correlation existed between DRSi and salinity in surface waters (Figure 11) though it was apparent that assimilation, re-mineralisation and, on occasion, advection of water relatively enriched with silica from offshore also played a role in influencing the observed distributions.

# 3.1.3 Inorganic phosphorus

Concentration gradients of dissolved reactive phosphorus (DRP) were the least predictable and explicable of all the dissolved inorganic nutrient parameters. Although inshore to off-shore gradients existed (Figure 5C), their magnitude was frequently not large and at no time was this element below the limits of analytical detection in surface or sub-surface waters. There was no apparent correlation between salinity and DRP (Figure 11B) 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 (Figure 5C) at the same time as the mid winter 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 DRP concentrations were almost always found within the plumes of the Nelson Haven and Waimea and Moutere Inlets but most often concentrations within the highly turbid plume of the Motueka River were low. A mid-Bay NW/SE orientated surface water concentration maximum, approximately aligned along the 15 m depth contour as shown for 19-20 July (Figure 5C), was observed on six of the eleven sampling surveys.



#### 4 **DISCUSSION**

Based on the present, limited, data set, a number of hypotheses can be drawn that provide a framework for understanding the role of river borne nutrients within the Tasman Bay ecosystem. These are described in the following sections.

#### 4.1 Inorganic nitrogen

The annual appearance of nitrite in the <30 m-deep water column is the single most predictable seasonal water chemistry marker for Tasman Bay, and it is clearly linked to the annual nitrate maximum. With the exception of trace amounts in deeper (>30 m) waters, Nitrite is undetectable throughout the water column during most of the year. In April-May, concentrations begin to increase in deep, near-bottom waters and this increase progressively spreads into shallower areas until, by mid winter, nitrite is present in significant amounts (0.1-0.6 mmol-N m<sup>-3</sup>), throughout the water column, over the entire Bay. Nitrate concentrations follow a similar but somewhat less predictable pattern. Throughout the water column for much of the year, nitrate 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 is undetectable in freshwater inputs under all flow regimes and at all times of the year. The water column nitrite maxima in the Bay are therefore obviously generated *in situ*.

The development of the nitrate/nitrite maximum is open to several interpretations. It is most likely due to the suppression of phytoplankton photosynthesis and nutrient assimilation as a result of seasonal light limitation to the extent that the rates of (light independent) nitrogen re-mineralization and transformation processes within the water column and sediments become dominant. Biological processes which lead to the appearance of nitrite in the coastal water column are denitrification, including assimilatory and dissimilatory nitrate reduction (Hattori 1983), and nitrification by ammonium oxidation (Kaplan 1983). Nitrite accumulation occurs when the rate of one or other of these processes exceeds the capacity of algae or bacteria to assimilate it (Kamykowski and Zentara 1991). It has been shown using tracer methods (Ward *et al.* 1989), that the production of nitrate in the water column can be detected even when nitrate concentrations are declining due to phytoplankton assimilation. There is strong support for the notion that nitrification is the dominant process in determining the profiles of nitrite in coastal and offshore waters (Holligan *et al.* 1984).

The potential importance of bacterial nitrification in supplying regenerated nitrate to the phytoplankton with the euphotic zone has been demonstrated in New Zealand waters by the measurement of nitrogen uptake and ammonium oxidation rates and nitrous oxide levels in off shore Tasman Bay in western Cook Strait (Priscu and Downes 1985). They suggested that ammonium oxidation by nitrifying bacteria may account for about 30% of the total ammonium utilisation (i.e. bacterial and algal) and may supply about 40% of the phytoplankton nitrate requirements. Likewise, Dore and Karl (1996) demonstrated in tropical oceanic waters that nitrification in the euphotic zone is an important source of regenerated nitrate. They estimated that nitrate regeneration by nitrification may be 47-142% of the concurrent nitrate 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, except in deeper water below the euphotic zone, they do not accumulate. In Tasman Bay, there is evidence to suggest that the close dynamic relationship between nitrification and nitrogen assimilation occasionally becomes uncoupled due to transient slow-downs in assimilation rate due to limitation by other essential elements, of which the most likely is phosphorus. It is believed that this is the reason for the peaks in nitrate that occasionally appear during summer (e.g. December1993) in Tasman Bay waters



(Figure 3). 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) have identified mid summer 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 result in the water column being stripped of inorganic phosphorus, which is deposited on the sediments, with a concurrent rise in the levels of nitrate as the phytoplankton become limited by phosphorus, and nitrogen assimilation rates decline.

# **Definition Box 3: Microalgae**

**Phytoplankton** (or planktonic microalgae)- single-celled plants that live and grow while suspended in the water column.

**Benthic microalgae-** single-celled microscopic plants (mainly diatoms) that live and grow on the seabed.

**Diatoms-** a group of planktonic and benthic microalgae. They are an important component of temperate marine phytoplankton communities and, unlike other groups, they are encased in a rigid silicate frustule.

**Dinoflagellates-** a very diverse, group of planktonic and benthic microalgae. Many of the toxin-producing species of phytoplankton are within this group.

**Chlorophyll** *a* (chl *a*)- the primary photosynthetic pigment for green plants. It can be used as a relative estimate of the biomass (dry weight or carbon content) of microalgae in a water or sediment sample.

**Fluorescence-** Chl *a* can be estimated by measuring the amount of light emitted by living phytoplankton cells that are exposed to a beam of artificial light. This emission is called fluorescence and can be measured by lowering a submersible detector over the side of a boat. The fluorescence readings then need to be calibrated using normal laboratory analytical techniques.

**Euphotic zone-** the portion of the water column where sufficient sunlight penetrates to support the process of photosynthesis.

# CAWTHRON

# Technical Box 1: Fertility of the sea

In the sea, unlike on land, water is of course never a problem for plant growth and it is mainly the amount of light and the demand for mineral nutrients that most limits plant (i.e. phytoplankton) production. New Zealand pastoral soils are mostly deficient in phosphorus and farmers have to fertilise the land with this element, to grow grass, to feed their animals. Not much nitrogen fertiliser is directly applied to pastoral soils in New Zealand because this is mainly naturally supplied by nitrogen fixing bacteria, which are either free-living or associated with the roots of plants. In most temperate coastal sea-waters the situation is rather different. Phosphorus is usually quite abundant and plant growth is mainly limited by the amount of dissolved inorganic nitrogen that is available because nitrogen fixation (most nitrogen fixing bacteria cannot tolerate the high salt content of sea-water) hardly occurs at all. The essential nitrogen, in the form of nitrate (NO<sub>3</sub><sup>-</sup>-N) and ammonium (NH<sub>4</sub><sup>+</sup>-N), has to come either from deep ocean waters where these nutrients accumulate, from the land via freshwater runoff, from excretion by living plants and animals or from the bacterial decay of organic material in the water and on the seabed. Potassium and sulphur, which are often in short supply to land plants, (and are liberally applied as fertilisers) are highly concentrated in sea-water, whereas other elements like iron and silica are important limiting nutrient elements in the sea but not on the land.

Land farmers can easily supplement soil nutrients but marine farmers have no effective controls on the mineral supply. They rely on natural processes such as deep water upwelling, floods and microbial re-mineralisation to fertilise their crops. Because there is not a lot that can be practically done to artificially stimulate phytoplankton production, the siting of shellfish farms in naturally fertile areas and the manipulation of stocking density are the only ways to optimise the amount of food available.

# 4.1.1 Atmospheric nitrogen deposition

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 (Paerl *et al.* 1990). In this context, inputs of up to 16.6 mmol-N m<sup>-2</sup> month<sup>-1</sup> (or about 30% total N input load and 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 (MacKenzie unpubl.) have varied from undetectable to 2.6 mmol-N m<sup>-3</sup>. Given an average rainfall in Nelson of 975 mm/year, the quantity of atmospheric nitrogen deposition on the Tasman Bay study area could be as much as 66 kg-N/day or about 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.

## 4.1.2 Sediment nitrogen recycling and denitrification

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, over most of the study area, the euphotic zone encompasses the entire water column (Gillespie 2003) 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 maxima. The net effect of sediment nutrient re-mineralization could be observed in turbid near shore locations (5-10 m) within the water column profiles off the Motueka River mouth (Figure 7, Figure 8) where near bottom DIN concentrations were often significantly elevated. Christensen *et al.* (2003) have shown that at one 20-24m deep site (T3) in Tasman Bay (site 7B in this study), the rates of  $O_2$ , 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 (Jan-Feb) and nutrient-replete (May-July) periods (Table 4) with potential inorganic nitrogen sources (rivers, sediment efflux) and sinks (denitrification).

Direct estimates and biogeochemical modelling studies on similar ecosystems elsewhere suggest that denitrification in the sediments of coastal/shelf seas are significant global-scale sinks of combined nitrogen (Seitzinger and Giblin 1996, Hydes et al. 1999). If we consider the area of Tasman Bay within the 30 m bathymetry range, it is clear that the loss of nitrogen via denitrification more than compensates for the present rate of DIN inflow from all freshwater sources. To illustrate this, the estimated loss via denitification is more than four times the freshwater delivery rate. By comparison, in a variety of coastal systems elsewhere where catchment N-delivery rates are much greater, sediment denitrification is not an effective counterbalance for the processes of eutrophication. For example, Seitzinger (2000) reports that, in 10 of 14 systems studied in North American and European waters, <50% of the DIN inflow was removed by denitrification. Studies of 10 Danish fjords (P. Christensen, National Environmental Research Institute, Denmark, pers.com.) showed that, on average, only about 20% of the N-inflow was denitrified. In most of the Danish systems, agricultural nutrient sources have resulted in significant coastal eutrophication. Thus the receiving environment of Tasman Bay seems able to cope with the present level of Ninflow from its catchment without danger of the classical symptoms of accelerated nutrient enrichment seen in many similar coastal locations in other parts of the world.

Although these are approximations, and only provide a snap shot in time of the net effects of highly dynamic bio-geochemical processes, they raise questions as to the relative significance of the river inputs with respect to phytoplankton production. On average, the amount of inorganic nitrogen entering the study area in the river waters is less than half of the amount of nitrate and ammonium released from the sediments. Clearly, to provide the bulk of the inorganic nitrogen that contributes to the winter nitrate/nitrite maxima (*e.g.* 533 tonnes-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 (MacKenzie *et al.* in prep.), the high suspended sediment loads and the contribution of other essential elements (*e.g.* Fe and Si), that can be important regulators of phytoplankton production.

Depth Range	Area (km <sup>2</sup> )	9-10 Jan 96	22-23 Feb 96	15-16 May 96	19-20 Jul 96	Sediment efflux *	Sediment denitrification*	TB rivers, mean influx (1995-96)		
	$NO_3^{-} + NO_2^{-}$ (tonnes-N)						Tonnes-N/day			
20-30m	225.2	25.3	34.8	80.2	260.5					
10-20m	220.4	11.5	31.4	37.0	190.4					
5-10m	95.7	7.2	8.3	13.8	66.5					
<5m	62.4	1.8	3.1	3.9	15.7					
Total	633.7	45.8	77.6	134.9	533.1	2.6	5.1	1.2		

**Table 2.** Bulk quantities of nitrate-N and nitrite-N in the water column of the Tasman Bay study area (<30 m) during summer (Jan & Feb 1996) and autumn/winter periods (May & July 1996), relative to approximations of DIN influx from the rivers, and sediment efflux and denitrification.

\* Calculated from values in Christensen et al. (2003).

#### 4.2 Inorganic silicates

Data from transect 7 (Figure 9) clearly illustrates the impact of the Motueka River plume on surface and near surface silica concentrations. Mid-water and near-bottom silica concentration maxima during the warmer months of January, February and March were suggestive of temperature dependant re-mineralisation processes taking place at these times. The low dissolved reactive silica concentrations observed in the mid-upper water column during May (Figure 9), and the persistence of low deep-water concentrations during the winter (July and August), is suggestive of silicate draw-down due to an autumnal diatom-dominated phytoplankton bloom which occurred at this time. Benthic diatom growth on the seabed (Gillespie 2003) is also a likely contributor to such a draw-down mechanism.

## 4.3 Freshwater nutrient inflow

One objective in this study was to obtain data that would lead to a better perspective on the significance of freshwater nutrient inputs to Tasman Bay seawaters relative to enrichment from other sources. In enclosed waters such a the Rhode River estuary (Jordan *et al.* 1991), long term (>18 yr) monitoring has shown that the magnitude of seasonal changes in phytoplankton biomass are directly correlated with the magnitude of river flows of the previous spring. Together with seasonal changes in inorganic N:P ratios, this leads to the hypothesis that spring chlorophyll concentrations in that estuary are controlled by riverine nitrate inputs while, in summer, they are controlled by the regeneration of inorganic N from organic matter produced in the spring. So far there is insufficient data to substantiate this hypothesis in Tasman Bay, which is an open system where the cause and effect relationships may be somewhat less direct. An estimated residence time of approximately two months (Heath 1973), however, would indicate sufficient time for phytoplankton to respond to freshwater nutrient inflows within the Bay.

The inorganic nutrient ion concentrations in the surface sea-waters of Tasman Bay are significantly affected by freshwater runoff from contributing catchments, however the actual concentrations are very much lower than those encountered in similar locations elsewhere which are subject to high levels of agricultural, industrial and urban pollution. In San Francisco Bay, California, for example, typical winter levels of NO<sub>3</sub><sup>-</sup>-N, NH<sub>4</sub><sup>+</sup>-N, DRSi, and DRP are 40-80, 10-15, 70-130, and 5-10 mmol m<sup>-3</sup>, respectively (Cloern 1996). For all but silica; these are up to an order of magnitude above the maximum levels observed in Tasman Bay.

The influence of the low salinity river plumes was apparent in the molar ratios of the inorganic macro-nutrients (Table 2) in seawater throughout the study area. DIN:DRP ratios were always higher in surface waters than at depths due to the relative enrichment of DIN over DRP in



freshwater inflows. Conversely DIN:DRSi ratios were lower in surface sea water throughout the Bay due to the relative enrichment with DRSi in freshwaters. Inorganic nitrogen, silica and phosphorus ratios in the Motueka River (Table 2) are typical of those observed in pristine river environments (*e.g.* the MacKenzie and Yukon) compared to major river systems heavily impacted by anthropogenic inputs (*e.g.* the Seine and Rhine).

Location and date	DIN:DRP		DIN:DRSi		DRSi:DRP	
	0m	All depths except 0m	0m	All depths except 0m	0m	All depths except 0m
Sea waters						
Tasman Bay, 15-16 May 1996	7.4	5.6	0.21	0.29	35.2	19.4
Tasman Bay, 19-20 July 1996	13.5	7.3	0.29	0.69	46.5	10.6
Tasman Bay, 28-29 August 1996	4.5	3.7	0.09	0.24	50.2	15.5
Tasman Bay, 9-10 October 1996	8.8	4.6	0.26	0.28	33.7	16.4
River waters						
Motueka River, 1-8 October 1996	38.2	-	0.07	-	546.1	-
MacKenzie (Canada)*	37.5	-	0.05	-	752.0	-
Yukon (Alaska)*	23.9	-	0.03	-	786.0	-
Rhine (Germany)*	22.1	-	2.50	-	9.0	-
Seine (France)*	18.6	-	3.30	-	6.0	-
Mississippi (USA)*	15.0	-	1.10	-	14.0	

Table 3. Inorganic nitrogen, silica and phosphorus molar ratios

\* After Justic et al. (1995)

The inorganic nutrient loads carried by the main freshwater tributaries that discharge into Tasman Bay were calculated from historical data (Figure 12) and data from analyses of Motueka River waters at intervals over two flood events between 1 and 8 October 1996 (Figure 13). The assumption was made that nutrient concentrations in the smaller rivers were the same as those in the Motueka River, however this probably results in a slight underestimate of the total loadings, particularly in terms of DRP (see Section 3.1.3). Concentrations of nitrate-N and DRSi were lowest under extreme low and extreme high river flow conditions whereas ammonium-N and DRP concentrations were less predictably related to flow. To calculate the total nitrogen load, low flow (<10 m<sup>-3</sup> sec<sup>-1</sup>), medium flow (10-100 m<sup>-3</sup> sec<sup>-1</sup>), and high flow (>100 m<sup>-3</sup> sec<sup>-1</sup>) total dissolved inorganic nitrogen concentrations of 47.4, 154.8 and 75.7 mg N m<sup>-3</sup>, respectively, were applied 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<sup>-3</sup> and 3.5 g Si m<sup>-3</sup> respectively were used. During 1996, a relatively dry year, the nutrient loads were about 26% less than in 1995. The total DIN discharge was 513.8 and 379.2 tonnes N in 1995 and 1996, respectively (Table 2). Total DRP and DRSi discharges were 45.4 and 34.6 tonnes P and 1.6 x10<sup>4</sup> and 1.2 x10<sup>4</sup> tonnes Si in 1995 and 1996, respectively.

Table 4. Dissolved inorganic nutrient loads discharged into Tasman Bay in 1995 and 1996

	Total DIN load (tonnes N/yr)		Total D (tonne	RP load s P/yr)	Total DRSi load (tonnes x10 <sup>3</sup> Si/yr)	
_	1995	1996	1995	1996	1995	1996
Maitai River	23.4	13.0	2.4	1.3	0.8	0.5
Waimea River	131.3	75.9	29.6	25.4	10.4	9.0
Motueka River	334.2	290.3	11.2	6.2	3.9	2.2
Riwaka River	24.8	16.2	2.3	1.7	0.8	0.6
Total	513.8	379.2	45.5	34.6	15.9	12.3



Except in surface waters during mid winter flood events (e.g. July 1996; Table 2), inorganic N:P and N:Si ratios were significantly below the optimum Redfield ratios (16:1 and 1:1 respectively) for phytoplankton growth. N:P ratios in Motueka River waters, on the other hand, were high, and the inorganic nitrogen contents observed in the surface waters reflect the net effect of mixing of sea and river plume waters and phytoplankton assimilation. The ratios imply that a significant amount of nitrogen is selectively being removed from the system. They also imply that inorganic nitrogen is the element most limiting production in the region. However, as Geider and Roche (2002) have emphasised, the Redfield ratio does not reflect a fundamental constraint on the elemental composition of primary production, and 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). 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 cases may result in benthic hypoxia. It also selects for problematic flagellate species and reduces the role of diatoms in productivity. There are no 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).

# 5 SUMMARY

## 5.1 Background

The information provided in this report was collected as part of a collaborative research effort called the Motueka Integrated Catchment Management (ICM) programme. The programme was designed to assess the effects of various land use practices on terrestrial, freshwater and marine ecosystems in a *"ridge top to the sea"* approach. One component of a Cawthron Institute (Cawthron) investigation into the effects of freshwater inflow quantity and quality on the productivity of the marine receiving environment, is presented here. Other components are presented in a series of related (companion) reports.

## 5.2 Study objective

A series of synoptic surveys of surface and water column salinity fields and inorganic nutrient concentrations of Tasman Bay were evaluated. This investigation was carried out over a one-year period at seasonally representative times and during, and soon after, a range of flow regimes in the major freshwater tributaries of the Bay. The specific goal was to establish sufficient perspective on the nutrient structure and dynamics in Tasman Bay in order to contribute to the overall goal of assessing the relationships between the quantity and quality of the Motueka River and the productivity and ecosystem function of the Bay.

## 5.3 Nutrient dynamics

An assessment was made of the relative importance of external (*e.g.* river borne) and internal (*i.e.* recycling) nutrient sources that contribute to the fertility of Tasman Bay waters. Flood events in the

Bay's catchment caused significant changes in the concentrations of dissolved nitrogen, phosphorus and silica in surface waters, and on an annual basis, between 60% and 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 concentrations 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 suggest 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. Intermittently, at other times of year, phytoplankton productivity in surface waters is likely to be limited by the availability of nitrogen. Preliminary calculations indicate 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. The loss of nutrient forms of nitrogen from the Tasman Bay system via denitrification (calculated from Christensen et al. 2003), appears to be roughly four times greater than the delivery rate via river inflows. These results suggest that the presently existing land use characteristics of contributing catchments do not represent a serious threat in terms of potential over-enrichment of the Tasman Bay ecosystem.

The nutrient concentrations reported here for Tasman Bay seawaters, though brief snapshots in time, clearly show the influence of freshwater tributaries (particularly the Motueka River) and put flesh on the bones of previous research and monitoring at a few sites. They represent the net effect of transport of these nutrients into and out of the Bay via rivers and ocean currents and internal assimilation, storage and regeneration processes in the water column and sediments. They provide better perspective on the relative importance of the various sources of inorganic nutrients that drive the productivity of the system. This helps to build a more coherent picture of the effects of episodic flood events superimposed on underlying seasonal hydrographic and biogeochemical processes, and contributes to validation of hydrodynamic and ecosystem models of Tasman Bay and adjoining regions.

# **6** ACKNOWLEDGEMENTS

Work was undertaken on the vessel *Idle Gossip*, owned and operated by Brydon Banks, Nelson and Cawthron's research vessel, *RV Gannet*. The authors thank Aaron Quarterman, Rod Asher, Steven Brown and Graeme Bloomfield for assistance with sampling, Toni Dees and her colleagues in the Cawthron water lab for carrying out the nutrient analyses. This research was carried out under contracts CAW-607, CAW805 and CO9X0014 to the NZ Foundation for Research Science and Technology.



#### 7 REFERENCES

- Bedding, S.; Brockman, U.; Dannecker, W.; Korner, D.; Pohlman, T.; Puls, W. Radach, G.; Rebers, A.; Rick, H. J.; Schatzmann, H.; Schulz, M. 1997: Nitrogen fluxes in the German Bight. *Marine Pollution Bulletin* 34: 382-394
- Biggs, B. J. F.; Gerbeaux, P. 1993: Periphyton develoment in relation to macroscale (geology) and micro-scale (velocity) limiters in two gravel-bed rivers, New Zealand. New Zealand Journal of Marine and Freshwater Research 27: 39-53
- Bradford, J. M.; Lapennas P. P.;. Murtagh R. A.; Chang F. H.; Wilkinson V. 1986: Factors controlling summer phytoplankton production in greater Cook Strait, New Zealand. *New Zealand Journal of Marine and Freshwater Research* 20: 253-279
- Bradford-Grieve, J.; Bull, M.; Drummond, K.; Gordon, D.; Laing, A.; Mackenzie, L.; Moore, M.;
  Murdoch, R.; Nodder, S. 1994: Summary of Knowledge of the Tasman Bay and Golden
  Bay Marine Environment relevant to Fisheries Enhancement. A report for Southern
  Scallop Fishery Advisory Committee, MAF Fisheries and the Tasman District Council
  179 pp. plus Appendices
- Christensen, P. B.; Glud, R. N.; Dalsgaard, T.; Gillespie, P. 2003: Impacts of longline mussel farming on oxygen and nitrogen dynamics and biological communities of coastal sediments. *Aquaculture* 218: 567-588
- Cloern, J. E. 1996: Phytoplankton bloom dynamics in coastal ecosystems; a review with some general lessons from sustained investigation of San Fransico Bay, Califonia. *Reviews of Geophysics* 34: 127-168
- Close, M. E.; Davies-Colley, R. J. 1990a: Base flow water chemistry in New Zealand rivers. 1. Characterisation. New Zealand Journal of Marine and Freshwater Research 24: 319-341
- Close, M. E.; Davies-Colley, R. J. 1990b: Base flow water chemistry in New Zealand rivers. 2. Influence of environmental factors. *New Zealand Journal of Marine and Freshwater Research* 24: 343-356
- Dore, J. E.; Karl D. M. 1996: Nitrification in the euphotic zone as asource for nitrite, nitrate and nitrous oxide at station ALOHA *Limnology and Oceanography* 41: 1619-1628
- Geider, R. J., La Roche, J. 2002. Redfield revisited: variability of C:N:P in marine microalgae and its biochemical basis. *European Journal of Phycology* 37: 1-17
- Gibbs, M.; Ross, A.; Downes, M. 2002: Nutrient cycling and fluxes in Beatrix Bay, Pelorus Sound, New Zealand. New Zealand Journal of Marine and Freshwater Research 36: 675-698
- Gibbs, M. 2001: Sedimentation, suspension and resuspension in Tasman Bay and Beatrix Bay, New Zealand, two contrasting coastal environments which thermally stratify in summer. *New Zealand Journal of Marine and Freshwater Research* 35: 951-6970
- Gillespie P. 2003. Benthic and planktonic microalgae in Tasman Bay: Biomass distribution and implications for shellfish growth. Report prepared for Stakeholders of the Motueka Integrated Catchment Management Programme. *Cawthron Report No.* 835. 25p + Appendices.
- Hattori, A. 1983; Denitrification and dissimilatory nitrate reduction. *In*: Carpenter E. J., Capaone, D. G. [eds] *Nitrogen in the Marine Environment* Academic Press New York. pp 191-232
- Heath, R. A. 1973: Meteorological effects on the surface circulation and hydrology of Tasman Bay, New Zealand. *New Zealand Journal of Marine and Freshwater Research* 7: 111-123



- Heath, R. A. 1976: Circulation in Tasman Bay. New Zealand Journal of Marine and Freshwater Research 10: 469-483
- Heath, R. A. 1979: Resonant over-tide across and along Tasman Bay, New Zealand. *Estuarine and Coastal Marine Science* 8: 583-595
- Hickel, W.; Mangelsdorf, P.; Berg, J. 1993: The human impact in the German Bight: Eutrophication during three decades (1962-1991). *Helgolander Meeresunters* 47: 243-263
- Holligan, P. M.; Balch, W. M.; Yentsch C. M. 1984: The significance of subsurface chlorophyll, nitrite and amonium maxima in relation to nitrogen for phytoplankton growth in stratified waters of the Gulf of Maine. *Journal of Marine Research* 42: 1051-1073
- Hydes, D. J.; Kelly-Gerreyn, B. A.; Le Gall, A. C.; Proctor, R. 1999: The balance of supply of nutrients and demands of biological production and denitrification in a temperate latitude shelf sea a treatment of the southern North Sea as an extended estuary. *Marine Chemistry* 68: 117-131
- Jickells, T. D. 1998: Nutrient biogeochemistry of the coastal zone. Science 281: 217-222
- Jordan, T. E.; Correll, D. L.; Miklas, J.; Weller, D. E. 1991: Long-term trends in estuarine nutrients and chlorophyll, and short-term effects of variation in watershed discharge. *Marine Ecology Progress Series* 75: 121-132
- Justic, D.; Legovic, T.; Rottini-Sandini, L. 1987: Trend in the oxygen content 1911-1984 and occurrence of benthic mortality in the Northern Adriatic sea. *Estuarine, Coastal and Shelf Science* 25: 435-445
- Justic, D.; Rabalais, N. N.; Turner, R. E.; Dortch, Q. 1995: Changes in Nutrient Structure of Riverdominated Coastal Waters: Stoichiometric Nutrient Balance and its Consequences. *Estuarine, Coastal and Shelf Science*. 40: 339-356
- Justic, D.; Turner, R. E.; Rabalais; N. N. 2003: Climatic influences on riverine nitrate flux: Implications for coastal marine eutrophication and hypoxia. *Estuaries* 26: 1-11
- Kamykowski, D.; Zentara, S. J. 1991: Spatio-temporal and process-orientated views of nitrite in the world ocean as recorded in the historical data set. *Deep Sea Research* 38: 445-464
- Kaplan W. A. 1983: Nitrification. In: Carpenter E. J., Capaone, D. G. [eds] Nitrogen in the Marine Environment Academic Press New York. pp 139-190
- Kattner, G. 1999: Storage of dissolved inorganic nutrients in sea water: poisoning with mercuric chloride. *Marine Chemistry* 67: 61-66
- Lohrenz, S. E.; Fahnenstiel, G. L.; Redalje, D. G.; Lang, G. A.; Chen, X.; Dagg, M. J. 1997: Variations in primary production of northern Gulf of Mexico continental shelf waters linked to nutrient inputs from the Mississipi River. *Marine Ecology Progress Series* 155: 45-54
- MacKenzie, A. L.; Gillespie, P. A. 1986: Plankton ecology and productivity, nutrient chemistry and hydrography of Tasman Bay, New Zealand 1982-1984. *New Zealand Journal of Marine and Freshwater Research 20*: 365-369
- MacKenzie, L.; Sims, I.; Beuzenberg, V.; Gillespie, P. 2002: Mass accumulation of mucilage caused by dinoflagellate polysaccharide exudates in Tasman Bay, New Zealand. *Harmful Algae* 1: 69-83



- MacKenzie, L.; *et al. in prep.* Water column stratification and the spatial and temporal distribution of phytoplankton biomass in Tasman Bay, New Zealand.
- Paerl, H. W.; Rudek, J.; Mallin, M. A. 1990: Stimulation of phytoplankton production in coastal waters by natural rainfall inputs: nutritional and trophic implications. *Marine biology* 107: 247-254
- Priscu, J. C.; Downes, M. T. 1985: Nitrogen uptake, ammonium oxidation and nitrous oxide (N<sub>2</sub>O) levels in the coastal waters of western Cook Strait, New Zealand. *Estuarine Coastal and Shelf Science 20:* 529-542
- Rabalais, N. N.; Turner, R. E.; Scavia, D. 2002: Beyond science into policy: Gulf of Mexico hypoxia and the Mississippi River. *BioScience* 52. 129-142
- Redfield, A. C.;Ketchum, B. H.; Richards, F. A. 1963. The influence of organisms on the composition of seawater. In *The Sea*, M. N. Hill (Ed.) vol. 2, pp26-77. New York, Wiley.
- Ridgway, N. M. 1977: Currents and hydrology in Tasman and Golden Bays, South Island, New Zealand. New Zealand Journal of Marine and Freshwater Research 11: 95-109
- Seitzinger, S. P.; Giblin, A. E. 1996: Estimating denitrification in North Atlantic shelf sediments. *Biogeochemistry* 35: 235-260
- Seitzinger, Sybil P. 2000. Scaling up: Site specific measurements to global-scale estimates of denitrification. Pp 211-237. *In* J. E. Hobbie (Ed), Estuarine Science: A Synthetic Approach To Research and Practice. Island Press, Washington, DC.
- Solarazano, L. 1969. Determination of ammonium in natural waters by the phenol-hypochlorite method. *Limnology and Oceanography*.14: 799-801.
- Strickland, J. D.; Parsons, T. R. 1968: A practical handbook of seawater analyses, 2nd edition. Bulletin of the Fisheries Research Board of Canada 167. 311 p.
- Ward, B. B.; Kilpatrick, K. A.; Renger, E. H.; Eppley R. W. 1989: Biological nitrogen cycling in the nitracline. *Limnology and Oceanography* 34: 493-513



**Figure 1.** Geographic location of Tasman Bay and major fresh water inputs, bathymetry (1A) and location of sample survey sites and transects (1B). Sites B1 ("Glen"), B4 ("Ruby Bay"), and B7 ("Bomber") were those used for routine long term monitoring. The 30m contour and 'Pitt Head' and 'Pepin Is.' boundaries define the limits of the study area.



**Figure 2.** The relative magnitude  $(m^3 \times 10^9 / \text{year})$  of the total annual discharge (2A) during 1995 and 1996 and combined total daily flows  $(m^3 \times 10^6 / \text{day})$  in the Motueka, Riwaka, Waimea and Maitai rivers during the sampling survey period (2B). The arrows on 2B represent the sample survey occasions.

July 2003

CAWTHRON









**Figure 3.** Average combined depth weighted mean nitrate-N and nitrite-N concentrations (mmol-N m<sup>-3</sup>) at sites B1, B2 and B7, 1991-1996.

Motueka Integrated Catchment Management Programme Report Series: River inputs, re-mineralisation and the distribution of inorganic nutrients in Tasman Bay





**Figure 4.** Combined depth weighted mean concentrations of water column properties at sites B4 and B7 Jul-Dec 1996. Chla and DRP (4A); Nitrate-N and Nitrite-N (4B); Ammonium-N (4C); DRSi (4D).



**Figure 5.** Plots of surface seawater properties during selected seasonal survey periods. 5A, surface salinity (psu); 5B, surface nitrate-N (mmol-N m<sup>-3</sup>); 5C, surface DRP (mmol-P m<sup>-3</sup>); 5D, surface DRSi (mmol-Si m<sup>-3</sup>).



Figure 5 Continued.



**Figure 6.** Water column profiles of salinity (psu) on Transect 7 off the mouth of the Motueka River, during selected synoptic surveys.





**Figure 7.** Water column profiles of nitrate-N (mmol m<sup>-3</sup>-N) along transect 7 off the mouth of the Motueka River during selected synoptic surveys.



**Figure 8.** Water column profiles of nitrite-N (mmol-N m<sup>-3</sup>) on transect 7 off the mouth of the Motueka river during selected synoptic surveys.



**Figure 9.** Water column profiles of DRSi (mmol-Si m<sup>-3</sup>) on transect 7 off the mouth of the Motueka river during selected synoptic surveys.





**Figure 10.** Plots of the sea-surface distribution and water column profiles of ammonium -N (mmol-N m<sup>-3</sup>) concentrations on two successive synoptic survey occasions (19-20 July 1996 and 28-29 August 1996).





**Figure 11.** Salinity and inorganic nutrient concentrations in surface waters for all data collected during synpotic surveys Each plot represents 441 individual data points. 5A: Nitrate-N, 5B: Dissolved reactive phosphorus, 5C: Dissolved reactive silica.





**Figure 12.** DIN concentrations versus flow in the Motueka River, data from Biggs and Gerbeaux (1993), Close and Davis Collie (1990) and analyses over two flood cycles in the Motueka River 1-8 October 1996.



**Figure 13.** Inorganic nutrient concentrations over two flood cycles in the Motueka River, 1-8 October 1996.