Origin and processing of nutrients in Golden and Tasman Bays

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Executive Summary

The marine productivity of Golden and Tasman Bays (the Nelson Bays) is central to a number of management issues in the Tasman District, including its valuable scallop fishery, a developing mussel industry and a wide range of other ecosystem services, such as those associated with Abel Tasman National Park and Farewell Spit Wildlife Sanctuary. To improve understanding of the Nelson Bays' productivity, I present here a budgetary analysis of the origin and processing of their nutrients. It is expected that the system-level perspectives provided will improve understanding of bay productivity by managers and so their ability to evaluate management priorities for the bays and their catchments.

Nutrients are introduced to the bays through freshwater inflows and oceanic supply. The bays are exposed to oceanic waters of western Cook Strait, which are modified by upwelling on the West Coast and in general carry high nutrient levels, thus representing a potentially strong nutrient source. The nutrient climate is also modified by freshwater and nutrient inflow from larger rivers (Aorere, Takaka in Golden Bay, Motueka, Wairoa in Tasman Bay) and many smaller rivers and streams. These rivers drain farmed catchments and are generally enriched with nutrients, so it is important to gauge their impact on bay waters. Accounting of the absolute and relative magnitudes of nutrient loading to the bays from the ocean and catchments will be an important part of providing managers with improved understanding of their productivity.

The budgets combined marine data collected in FRST-funded oceanographic studies with data from national archives on freshwater inputs, to construct water, salt and nutrient mass-balance analyses of the systems. Results from the Nelson Bays are compared with similar budgets from the Firth of Thames and with systems budgeted overseas, to place their functionality in broader context.

The budgeting method calculated the conservative flows and mixing of water and salt through each bay, and then used these to estimate the non-conservative flows, sources and sinks of carbon and nutrients in the systems. Averages for hydrological parameters were taken between November 2001 and Oct. 2002 (inclusive) to align with quarterly sea surveys over the same period. Surface and meteorological inflows of freshwater and nutrients were determined by combining NIWA GIS-based hydrometric tools (River Environment Classification, SPARROW, TOPNET) and NIWA and Tasman District Council (TDC) databases on flows and nutrient concentrations at gauged sites, to estimate bay-wide flows to terminal reaches of all rivers and streams. Groundwater and wastewater inputs were also assessed using TDC and other datasets.

Important budget results were:

- The average riverine inflows during the period of the study were 140 and 120 $m^3 s^{-1}$ to Golden and Tasman Bays, respectively. These flows supplied 1100 and 700 tonnes total nitrogen (TN)

y^{--1} to the bays per annum, 80% of which was dissolved inorganic nitrogen (DIN), of which 90% was NO_3^-. Groundwater and wastewater contributed relatively little to these totals.

- Mean water residence time of Golden and Tasman Bays were 11 and 41 days, respectively. The shorter time for Golden Bay was driven by its much smaller volume (13 vs 31 km^3), higher net residual freshwater flows, and probably by more intense tidal mixing, than Tasman Bay.

- Non-conservative fluxes of dissolved inorganic phosphorus (DIP) from the shelf into both bays indicated net formation of organic matter from inorganic constituents, and the net uptake of dissolved inorganic carbon (DIC). Thus, for the bays, production (*p*) of organic matter exceeded respiration (*r*) and (*p*-*r*), or net ecosystem metabolism (NEM), was positive (i.e., they were net-autotrophic). Golden Bay net autotrophy was more active than Tasman Bay (1300 vs 900 mmol DIC m^{-2} y^{-1}).

- Non-conservative fluxes of dissolved inorganic nitrogen (DIN) from the shelf into both bays showed that they were net sinks for DIN. After correcting for the uptake of DIN into production (as estimated by the DIP uptake), the residual DIN flux was interpreted as the difference between net system N fixation and denitrification (*nfix-denit*). The negative values of this parameter for the bays showed them to be net denitrifying, with Golden Bay more active than Tasman Bay (410 and 180 mmol N m^{-2} yr^{-1}, respectively). Accounting for organic fluxes had little or no effect on these rates (390 and 180 mmol N m^{-2} yr^{-1}, respectively).

- The net autotrophic (*p*-*r*) values for the two bays placed them well within the range of autotrophic ecosystem cases derived from 70 budgets in the global 'Land-Ocean Interactions in the Coastal Zone' budget database. Although the (*nfix-denit*) values from the bays were among the lower (less denitrifying) rates tabulated from this database, they were within the major mode of that distribution.

- Although not exceptional in the global context, there were important contrasts between Golden and Tasman Bays NEM and that of the Firth of Thames. The net autotrophy of the bays appears to be a consequence of two factors: (a) their heavy loading with DIN from the ocean and (b) relatively light loading with organic matter from catchments. In contrast, the Firth is highly net-heterotrophic, consuming substantial organic matter and producing inorganic nutrients and DIC. The intense heterotrophy of the Firth is driven by heavy loading with catchment-derived organic matter – the particulate organic loading to the Firth by its rivers was about 20 x that of the bays. This also drives more intense denitrification in the Firth than in the bays.

- The ratio of fluxes of DIN from rivers to the total riverine and oceanic flux (corrected for residual flow losses) was calculated, to evaluate the balance of riverine and oceanic DIN fluxes for each bay. For Golden Bay, the flux of DIN from rivers contributed about 12% of the total, with mixing between the bay and the shelf contributing 88%. For Tasman Bay the contribution by rivers was 9%, with the ocean contributing the remainder. Additions of groundwater and wastewater to the catchment loads made negligible differences to these percentages. This demonstrated the dominance (~90%) of ocean supply of DIN to both bays, in setting their nutrient stock levels and in driving their potential nutrient variability. These findings contrast strongly with the Firth of Thames, where 50-70% of the DIN loading is riverine.

Resource management outcomes enabled by the budget results are as follows. First, the much faster water flux through Golden Bay than Tasman Bay could inform issues to do with marine farm effects, in terms of likelihood of formation of marine farm footprints and their persistence. Second, the findings for relative loadings among sources (river, groundwater and wastewater) informs catchment development and wastewater management policies - in general, riverine point source effects are likely to dominate those of groundwater and wastewater. Finally, the findings suggest that pastoral catchment development has exerted strong effects on the Firth of Thames ecosystem historically, and that the Firth will respond to catchment management policy to the extent that it affects nutrient loading. On the other hand, from a bay-wide, system-level perspective, it is oceanic supply which dominates the nutrient systems of Golden and Tasman Bays. Other factors being equal, variability in this source would be critical in setting productive conditions in the Nelson Bays over time-scales relevant to large secondary consumers including shellfish. This is a clear signal that managers should obtain improved understanding of oceanic processes in this region, to enable improved prediction of its ecosystem services.

1. Introduction

The marine productivity of Golden and Tasman Bays (the Nelson Bays) is central to a number of management issues in the Tasman District, including its valuable scallop fishery, a developing mussel farming industry and a wide range of other ecosystem services, particularly those associated with marine areas of Abel Tasman National Park and Farewell Spit Wildlife Sanctuary. All these natural amenities are founded on the productivity of the Nelson Bays' ecosystems. To improve understanding of the bays' productivity, I present here a budgetary analysis of origin and processing of their nutrients. It is expected that this will improve understanding of bay productivity by managers and their ability to evaluate management priorities for the bays and their catchments.

Nutrients are introduced to the bays through freshwater inflows and oceanic mixing. On the ocean side, the bays are exposed to western Cook Strait waters (Figure 1), derived from subtropical waters of the central Tasman Sea. These waters are manifested locally as an extension of the D'Urville Current which flows north up the South Island West Coast and retroflects into western Cook Strait (Harris 1990). They are periodically influenced by upwelling in the Kahurangi region, and the signal of upwelling is often observed in the waters advected into the western Strait. Even under non-upwelling conditions, the deeper parts of these water columns below the depth of net nutrient uptake have high nutrient concentrations, representing a potentially strong source of nutrients for the bays. The hydrodynamic exposure of the bays to these adjacent water masses means it is important to understand oceanic influence on the bays' ecosystems, nutrient supply and productivity.

Each bay has freshwater and nutrient contributions from two main rivers: the Aorere and Takaka rivers into Golden Bay and the Motueka and Wairoa rivers into Tasman Bay, as well as many smaller rivers and streams (Figure 1). The lower catchments of these rivers are to a greater or lesser degree invested with horticulture, while their hinterlands are in exotic forestry, native forest or scrub. There is also groundwater exposure to the sea in both bays. Because the rivers and groundwater entering the bays drain intensively farmed catchments and are generally enriched in nutrients, resource managers have an interest in gauging their impact on bay waters.

In this study water, salt and nutrient budgets provide system-level perspectives on important features of the bays, including their sensitivity to variable loading from oceanic and catchment sources. To do this, they combine marine data collected from the bays in FRST-funded oceanographic studies (Zeldis and Gall 2005; Figure 2), with data from national archives on freshwater inputs.

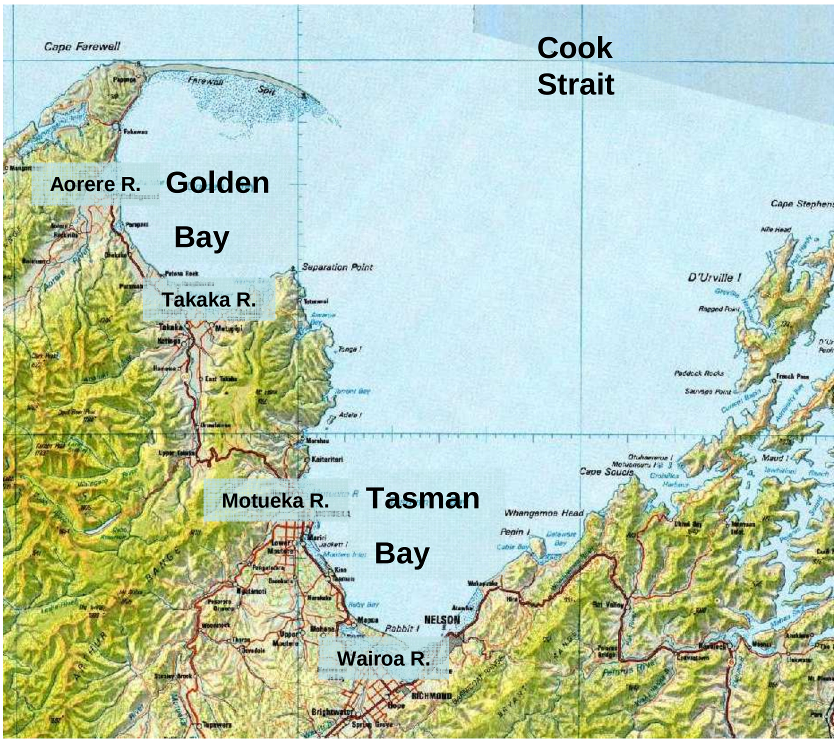

Figure 1: Cook Strait, Golden and Tasman Bays showing major rivers draining to each bay.

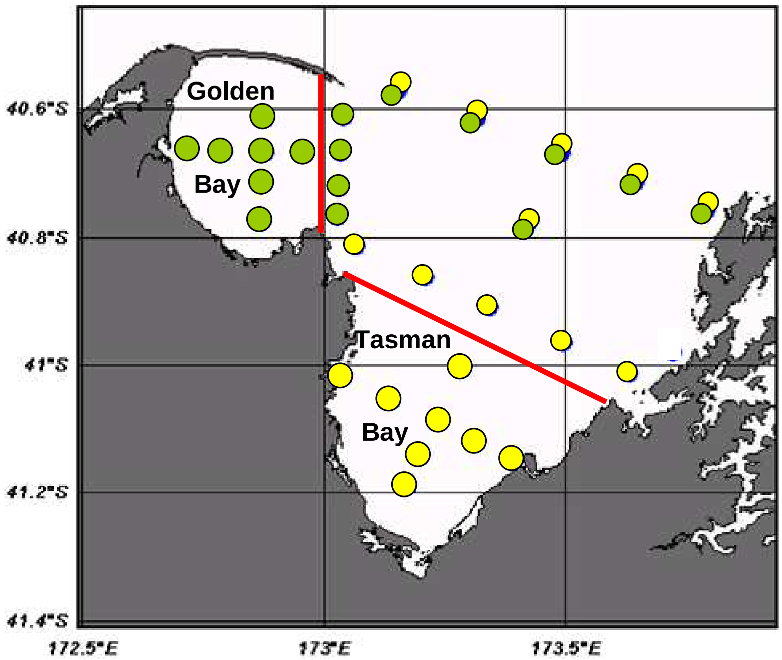

Figure 2: Golden and Tasman Bays, with all sampling stations sampled over seasonal voyages made 8-12 Dec. 2001 (KAH0110), 25-29 Mar. 2002 (KAH0202), 8-13 Jul. 2002 (KAH0207), and 30 Aug.-3 Sep. 2002 (KAH0211). Red lines define bay system outer boundaries. Green and yellow symbols mark stations used to describe conditions inside and outside Golden and Tasman Bays, respectively.

The budgeting protocol used was similar to that in Zeldis (2005, 2008), in which Firth of Thames and Hauraki Gulf physical and nutrient dynamics were described. Outcomes of that work included descriptions of the balance of terrestrial and oceanic forcing of nutrient flux (Hauraki Gulf Forum 2004), estimates of the amounts of externally-supplied carbon and nitrogen required to fuel the Firth and Gulf ecosystems (Zeldis 2006), and evaluations of aquaculture impacts on the Firth ecosystem (Zeldis 2005, 2008).

These outcomes were realised by describing nutrient sources, sinks and internal processing in the Gulf and Firth systems. A particularly important finding was that the major rivers draining into the Firth from the Waikato District contributed about 75% of the total of river + ocean dissolved inorganic nitrogen (DIN) supply to the Firth, while mixing across the marine boundary between the Firth and the seaward Hauraki Gulf contributed the remainder. The Firth was shown to efficiently process the heavy nutrient load it receives from its pastoral rivers (Waihou and Piako), through intense oxidation of organic matter and denitrification of nitrogen. The above percentages were sensitive to oceanographic conditions: when upwelling over the shelf was active, the ocean contributed about half of the DIN to the Firth. For the greater Hauraki Gulf, the budget showed that rivers (including those discharging to the Firth) supplied only 8% of DIN, and sewage from Auckland City contributed 5%, demonstrating the dominance of supply from the adjacent continental shelf.

In the present study, results from Tasman and Golden Bays are compared with those from the Firth, and with systems budgeted overseas, to place their functionality in broader context. Although neither the Firth nor Nelson Bays systems are found to be exceptional in the broad picture, fundamental differences between them are revealed that indicate important contrasts in conditions across the land-ocean boundaries of these respective New Zealand systems.

2. Methods and results

2.1. Overview

I first present a general overview of the budgetary approach, followed by detailed methods specific for the Tasman and Golden Bay cases. The work uses a class of mass-balance budgets known as "stoichiometrically linked water-salt-nutrient budgets" (Gordon et al. 1996), used extensively within the 'Land Oceans Interactions in the Coastal Zone' (LOICZ) programme of the International Geosphere-Biosphere Programme (IGBP). The nutrients of specific interest are carbon (C), nitrogen (N) and phosphorus (P). For each bay, the method is comprised of a series of budgets which are solved in a prescribed order (after Gordon et al. 1996).

2.1.1. Water budget

A budget is established of freshwater flows into and out of each bay system (Figure 2) comprising river runoff, groundwater, wastewater, precipitation and evaporation. There must be compensating outflow to the adjacent shelf system, to balance the net freshwater volume flowing into the bay. This is the 'residual' flow of water (Figure 3). Residual flow, V_R, for each bay system was calculated as:

$$V_R = -(V_Q + V_O + V_G + V_P + V_E)\,, \tag{1}$$

where subscripts *R*, *Q*, *O*, *G*, *P* and *E* identify volumes of total residual flow, river runoff, wastewater, groundwater, precipitation, and evaporation, respectively. Note that in this budget V_E terms are negative. Because residual flow is out of each bay, V_R is negative.

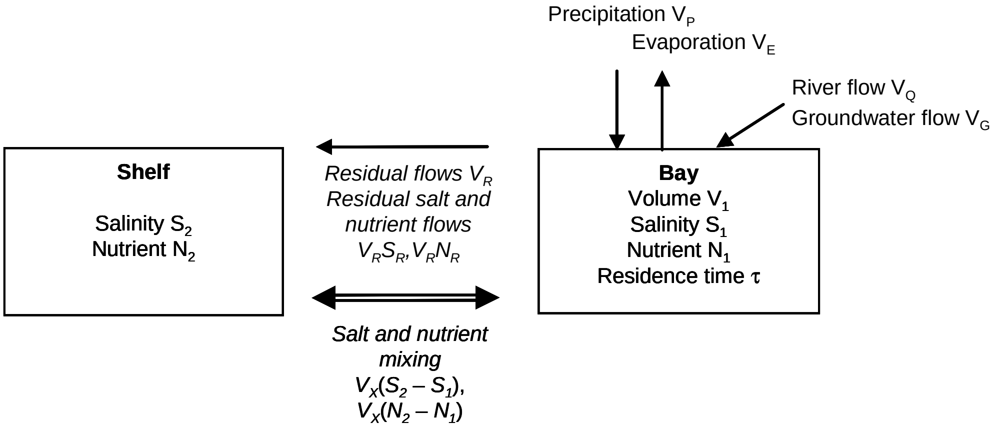

Figure 3: Schematic diagram of system boxes used in the LOICZ budget. Conservative flows of freshwater, salt and nutrients are shown with terms defined in text.

2.1.2. Salt budget

Salt must be conserved in the system when system volume and salinity are at steady state. Therefore, salt removed from the bay by the residual flow to the shelf must be replaced by mixing between the shelf and the bay, to sustain the salinity difference observed between the two systems (Figure 3). The water and salt budgets therefore calculate the exchange of water between the bay and shelf systems due to the processes of advection and mixing. The steady-state balance of salt between each bay and its respective shelf area (Figure 2) can be defined by:

$$0 = V_R S_R + V_X (S_1 - S_2)\,, \tag{2}$$

where the salinity of the residual flow (S_R) is the average of salinities of bay waters (S_1) and shelf waters (S_2), respectively. Rearrangement of this expression allows calculation of V_X, the mixing between bay and shelf waters required to balance the residual flows of salt. The mean residence time (τ) of water in each bay (with volume = V) is calculated as:

$$\tau = \frac{V}{\left(V_X + |V_R|\right)}. \tag{3}$$

2.1.3. Budgets of non-conservative materials

Dissolved materials (C, N, P) will exchange between the waters of Cook Strait and each bay due to the conservative residual and mixing flows described above (Figure 3). Deviations of material concentrations from predictions based on the previous steps are attributed to net non-conservative reactions of C N and P in the system. These terms are represented by the inputs and outputs shown below. At steady state the flux of these reactive materials includes an additional term, ΔY, to account for the net non-conservative fluxes (release - uptake) within the system:

$$\frac{VdY}{dt} = 0 = \sum V_{in} Y_{in} - \sum V_{out} Y_{out} + \Delta Y\ . \tag{4}$$

2.1.4. Non – conservative fluxes

Carbon metabolism

Net ecosystem metabolism (NEM) is the balance between net primary production and decomposition of organic material by the system, as represented by an equation of the form:

$$\begin{aligned} &106CO_2 + 16H^+ + 16NO_3^- + H_3PO_4 + 122H_2O \\ &\leftrightarrow (CH_2O)_{106}(NH_3)_{16}H_3PO_4 + 138O_2 \end{aligned}$$

This equation shows the relationships among C, N, P and oxygen typical of 'Redfield' molar ratios, for organic material found throughout much of the world ocean (with slight modification, such an equation can be written with NH_4^+ instead of NO_3^- as the nitrogen source, but the stoichiometry between C, N and P is unchanged).

It should be noted that C has both aqueous and gas phases, namely dissolved inorganic C (DIC) and CO_2 gas which exchanges across the air-sea interface. This means that

NEM cannot be determined by C measurements in the budgeting method, which measures fluxes of dissolved materials only. However, because there is no gas phase for P flux, it may be used as a proxy for NEM, by using the Redfield relationship between C and P. That is, the non-conservative net flux of dissolved inorganic P (DIP) can be considered an approximation of net inorganic C metabolism, at the scale of the ecosystem (it is assumed that net non-conservative P sorption/desorption involving inorganic particles is negligible as is likely in aerobic water columns and surficial sediments, such as here; Gordon et al. 1995).

Thus, via the net DIP flux we may estimate the net rate at which DIC is either produced or consumed by the ecosystem, and thereby it's NEM. This means we can determine whether the system is a net consumer of organic matter (e.g., phytoplankton, detritus, dissolved organic matter) and a producer of inorganic dissolved nutrients and DIC (i.e.,'heterotrophic'), or a net producer of organic matter and consumer of inorganic nutrients and DIC (i.e., 'autotrophic'). These attributes are often related to the nature and intensity of the nutrient loading the system receives from land and sea (Borges 2005, Le Tissier et al. 2006). Furthermore, when the net DIC flux is added to independent estimates of the primary production (carbon fixation) rate of the ecosystem, the absolute rate of ecosystem respiration can be estimated.

Nitrogen metabolism

Nitrogen also has major flux pathways involving a gas phase during denitrification (i.e., evolution of N_2 gas) and its back-reaction, N fixation:

$$
\begin{aligned}
&(CH_2O)_{106}(NH_3)_{16}H_3PO_4 + 94.4HNO_3 \\
&\leftrightarrow 106CO_2 + 177.2H_2O + H_3PO_4 + 55.2N_2
\end{aligned}
$$

Again, however, the DIC: DIP flux ratio is preserved in this reaction, enabling the *expected* flux of N to be predicted from DIP flux, by using the Redfield C:N:P composition ratios of reactive organic particles. The deviation of the *observed* (i.e., budgeted) fluxes of DIN from that *expected* (based on net DIP flux) provides an estimate of net rate at which the system is either denitrifying or fixing N with respect to the atmosphere. Again, this attribute may be related to the nature and intensity of the nutrient loading the system receives from land and sea.

2.2. Application to Golden and Tasman Bays

The following sections describe the application of the budgeting procedure to Golden and Tasman Bays, and the results obtained.

2.2.1. System areas and volumes

The system boundaries of the bays (red lines, Figure 2) divide the bay systems from the shelf waters offshore. Golden and Tasman Bays have surface areas of 790 and 1320 km^2, and volumes of 13 km^3 and 31 km^3, respectively (U. Shankar, NIWA, pers. comm., April 2007), reflecting the shallower bathymetry of Golden than Tasman Bay.

2.2.2. Study timing

Averages for hydrological parameters were taken between November 2001 and Oct. 2002 (inclusive) to account for timing of the quarterly sea surveys (December 2001, March 2002, July 2002, September 2002) and allowing for 1 month lead-up time of hydrology (runoff/precipitation/evaporation) prior to the first ocean survey.

2.2.3. Surface freshwater and freshwater nutrients

The following sequential procedure was used to extract surface freshwater flows and nutrient loadings (Total N, DIN, the sum of dissolved organic N (DON) and particulate organic N (PON), DIP, and dissolved organic phosphorus (DOP)) at coastal terminal reaches of all rivers and streams entering Golden and Tasman Bays.

1. The River Environment Classification (REC) scheme (Snelder et al. 2004) was used to find geographic polygons draining to each bay inside the land boundaries of each bay (defined by the endpoints of the red system boundaries in Fig. 2);

2. The mean annual flows within all polygons were found and summed for each bay (Woods et al. 2006);

3. The flows predicted by (2) for 4 rivers with flow recorders (Aorere at Devils Boots, Takaka at Kotinga, Motueka at Woodstock, Wairoa at Irvines) were compared with recorded flows for the period of the study (November 2001-October 2002 incl.) to scale mapped mean flows to measured flows, over the region. These flow recorders monitored 68 and 77 % of the catchment areas of

Golden and Tasman Bays, respectively, and 60 and 68% of their respective catchment flows.

4. REC reaches that drain to the sea were found, and at each of these the average N load (tonnes y^{-1}) was extracted using output from SPARROW (NIWA 2004) which accumulates N loads down-catchment based on catchment characteristics, land-use and in-river parameters.

5. Flow and nutrient (DIN and DIP) data from NZ Water Quality Network (NZWQN) and Tasman District Council Surface Water Quality Measurement Programme (SWQMP) sites on 5 rivers (those given above plus Riwaka at Hickmotts) were plotted in flow-by-month, concentration-by month, and concentration-by-flow space. While there were noticeable seasonal patterns in both concentration- and flow-by-month, the peaks did not coincide, such that flow and concentration were only weakly correlated. Consequently, inputs arising from each river were calculated on the basis of month-specific average nutrient concentrations for the river in question, for use below.

6. At NZWQN and SWQMP recorder sites, monthly mean TN, DIN, TP and DIP concentrations from January 1999 to April 2005 were extracted and multiplied by monthly mean flows for each river to derive mean monthly loads, which were then summed to annual loads.

7. The figures in (6) do not represent the entire river-loading to the bays (see 3). Inputs from other parts of the catchments were derived from the Sparrow model. To provide for a degree of calibration in this exercise, the annual loads at NZWQN and SWQMP recorder sites were compared with SPARROW values extracted for the recorder sites, to yield a scaling coefficient for SPARROW values for the period of interest at the sites. The relationship for the 4 rivers with both flow and nutrient data recorded (Aorere, Takaka, Motueka, Wairoa) was: site TN = 0.80 SPARROW TN (r^2= 0.91, n=4), with negligible intercept.

8. SPARROW values of TN at the coastal reaches of all rivers draining to the bays were adjusted by the scalar derived in (7) to estimate TN at the coast, and summed across all rivers.

9. DIN concentrations were estimated from coastal reach TN sums based on the relations between DIN and TN determined at recorder sites for the 5 rivers with such nutrient data: DIN = 0.86 TN - 46.88 (r^2 = 0.79, n = 188).

10. DIP concentrations at the coastal reaches (which are not available from SPARROW) were determined by the ratios of DIN to DIP at the recorder sites for each of the 5 rivers. These were then weighted by flow in each river within each region (Golden: Aorere and Takaka rivers; Tasman: Motueka and Wairoa rivers), to arrive at a flow-weighted scalar between DIN and DIP for each region.

11. For each region, DON+PON loads summed for all coastal reaches were determined as the difference between TN and DIN at the coastal reaches (the data do not allow separation of DON and PON).

12. DOP was estimated from DIP at the coastal reaches using relationships between DIP and DOP from Aorere, Motueka, Riwaka and Wairoa rivers available in Close and Colley (1990), weighted by flow as in (11), in each region.

The average inflows during the period of the study were 140 and 121 $m^3 s^{-1}$ to Golden and Tasman Bays, respectively (Table 1). These flows supplied about 1100 and 700 tonnes TN y^{--1} to the bays (Table 1), about 80% of which was DIN, of which 90% was NO_3^-.

Table 1: Mean river flows and nutrient loads to Golden and Tasman Bays, November 2001-October 2002 (incl.). Data for the Firth of Thames are also shown, re-calculated from Zeldis (2005) for terminal (coastal, non-estuarine) Firth river reaches using SPARROW.

Region	Flow ($m^3 s^{-1}$)	TN ($T y^{-1}$)	DIN ($T y^{-1}$)	DIN ($mmol y^{-1}$)	DIP ($mmol y^{-1}$)	DON+PON ($mmol y^{-1}$)	DOP ($mmol y^{-1}$)
Golden Bay	140	1100	900	6.3E+10	1.3E+09	1.4E+10	1.7E+09
Tasman Bay	121	700	600	4.0E+10	9.8E+08	7.9E+09	1.9E+09
Firth of Thames	64	7000	3200	2.3E+11	7.9E+09	2.7E+11	5.9E+09

2.2.4. Groundwater and groundwater nutrients

Groundwater is an important component of the hydrology of the catchments, but is much less well understood than the surface water hydrology (Tasman District Council 2000). For the Motueka aquifer, it was assumed that the groundwater volume flowing to Tasman Bay was 2.5% of surface flow (Joseph Thomas, Tasman District Council pers. comm. May 2007). This amounted to ~ 50 million $m^3 y^{-1}$ for this aquifer. This was scaled by NO_3^- concentration = 1 g m^{-3} (estimated by New Zealand Geological and Nuclear Sciences (GNS) sampling made after 2001) from wells in the Motueka aquifer. The Waimea aquifer is considered 'blind' to the sea, so no flux was assigned to it. The Moutere is a deep aquifer, with low N content, so was neglected as a contributor (Ibid). The Takaka aquifer was assigned the same percentage runoff and NO_3^- concentration as the Motueka. The estimated NO_3^- loadings from the two aquifers were thus 1.6 x 10^9 and 3.6 x 10^9 mmol y^{-1} for the Takaka and Motueka systems, respectively, or 3 and 10%, respectively, of the catchment surface water DIN runoff in the two bays. DIP was usually below detection limits in groundwaters assayed by GNS, so was assigned no flux to the bays.

2.2.5. Wastewater and wastewater nutrients

Wastewater from sewage treatment plants (STPs) is discharged primarily through wetland seepage ponds at Motueka and oxidation ponds at Bells Island (Tasman Bay), and STPs at Takaka and Collingwood (Golden Bay). Data on water volumes and nutrient concentrations from these were assembled using information collected at various times (depending on the facility) between 2002 and the present. Although the water volume of wastewater is 4 orders below that of riverine input, dissolved P and N are highly concentrated in the effluent, so nutrient flux from this source is included in the calculations. DIP inputs were 4.0 x 10^7 and 6.8 x 10^8 mmol y^{-1} in Golden and Tasman Bays, respectively, while DIN inputs were 9.7 x 10^8 and 5.8 x 10^9 mmol y^{-1}, respectively (the larger inputs to Tasman Bay arise from the Bells Island STP near Nelson). DIP inputs from STPs were thus 3 and 70% of DIP fluxes from rivers in Golden and Tasman Bays, respectively. For DIN, the percentages were 1 and 14%.

2.2.6. Atmospheric deposition

Wet and dry atmospheric deposition of P and N were neglected as they are insignificant in this very clean air region.

2.2.7. Precipitation and evaporation

Data for coastal rainfall and evaporation were gathered from rainfall and evaporation GIS surfaces generated from hydrological interpolations from TOPNET (Bandaragoda et al. 2004) using 5 km-spaced climate data for cells adjacent to the coast of each bay. Averages were taken between November 2001 and Oct. 2002 (inclusive). Over-water evaporation over the bays was estimated as 0.7 times the coastal evaporation (M.Duncan, NIWA, April 2007). Mean annual rainfall was 1432 and 1062 mm y^{-1} in Golden and Tasman Bay coastal areas, respectively, and over-water evaporation was 638 and 674 mm y^{-1}.

2.2.8. Saltwater and marine nutrient sources

The marine component of the mass-balance budget was based on salinity and nutrient samples collected in quarterly oceanographic voyages throughout Golden and Tasman Bays (see Figure 2 and Zeldis and Gall 2005 for descriptions). For the mass balance, salinity and nutrient data over all depths, stations and voyages were arithmetically averaged in each bay and corresponding shelf stations (Fig. 2), to estimate annually-averaged salt and nutrient concentrations in each bay and its adjacent shelf waters. This involved 79 and 158 samples taken in Golden Bay and its shelf station set, respectively, and 103 and 160 samples taken in Tasman Bay and its shelf station set, respectively. These were divided nearly equally between the 4 voyages, except in December 2001 when rough weather caused 4 bay stations to be missed in Golden Bay and 4 shelf stations to be missed Tasman Bay. Salinities were determined from SeaBird 911 CTD output (e.g., Zeldis et al. 2004) and nutrients (NO_3^-, NH_4^+, DIP, Total Dissolved N and P) were assayed according to methods in Pickmere (1998). Dissolved organic N and P were determined by difference.

Figure 4 shows the distributions of salinity and the nutrients on transects running from inner bay to Cook Strait waters. As expected, there was lower salinity in bay waters than shelf waters. There was also less DIP and DIN in bay than shelf waters. There was less bay-shelf contrast for the organic materials. There were large pools of DIP and DIN in outer bay and shelf waters, reaching maxima adjacent to Cook Strait (Figure 4).

2.2.9. Water and Salt Budgets

River flows into Golden Bay were greater than into Tasman Bay, as was Golden Bay precipitation/evaporation balance. These factors, combined with the much smaller volume of Golden than Tasman Bay, caused its substantially shorter water residence time (τ; eqn. 3): 11 d in Golden Bay *vs* 41 d in Golden Bay (Figure 5). The mixing rates required to balance the residual flow losses of salt were therefore greater between Golden Bay and the shelf, than between Tasman Bay and the shelf.

2.2.10. Budgets of non-conservative materials

The non-conservative flux of DIP, ΔDIP (Figure 6) was evaluated as the sum of riverine, groundwater, wastewater, residual and mixing DIP flows (eqn. 4). The negative values of ΔDIP for Golden and Tasman Bays indicates that these systems

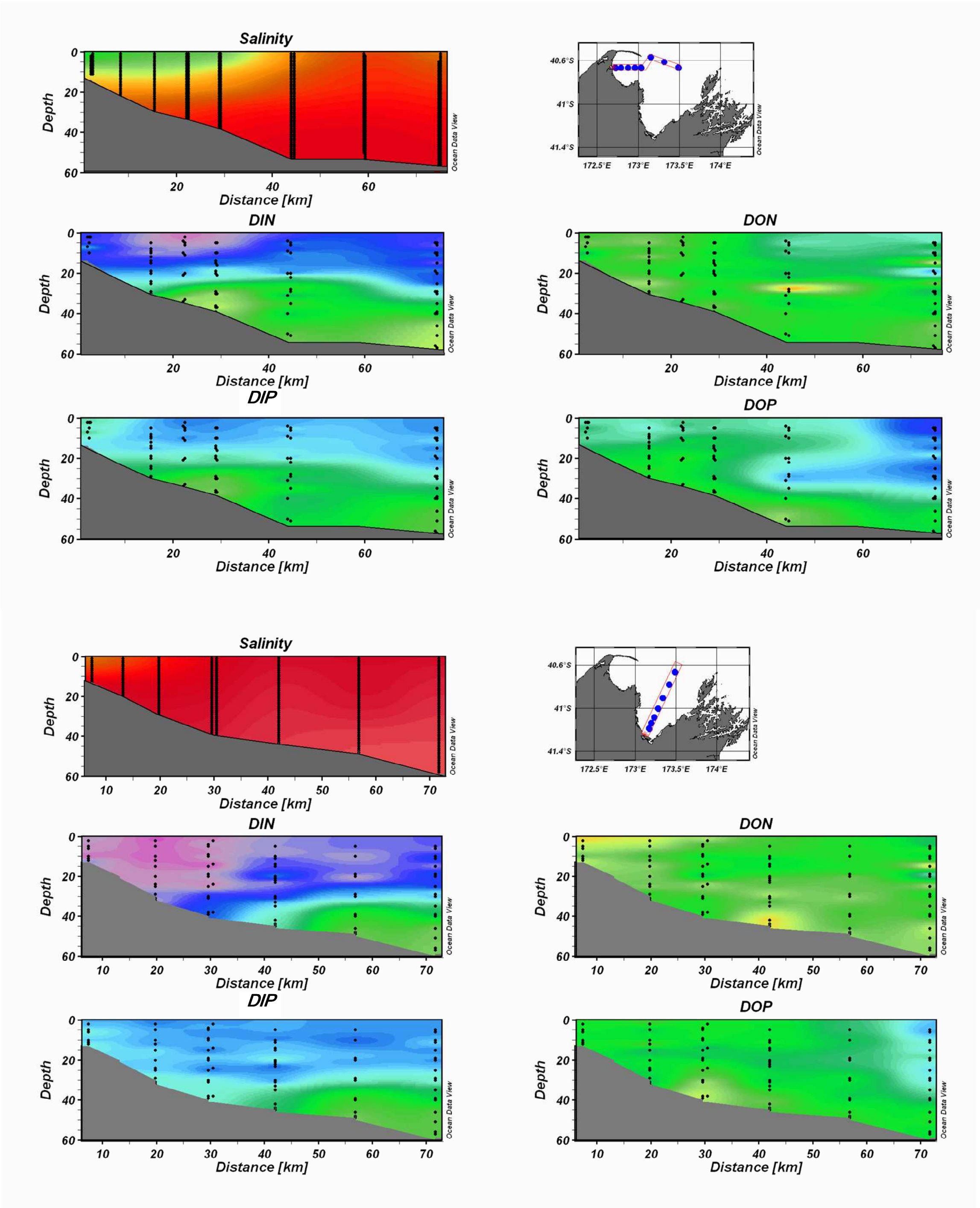

Figure 4. Annually-averaged vertical sections of properties inshore-offshore through Golden and Tasman Bays for salinity (psu), dissolved inorganic nitrogen (DIN), dissolved inorganic phosphorus (DIP), dissolved organic nitrogen and dissolved organic phosphorus (DOP) (mmol m^{-3}).). For each variable, colours show relative values of these quantities, increasing from purple through blue, green and yellow, to highest values in red.

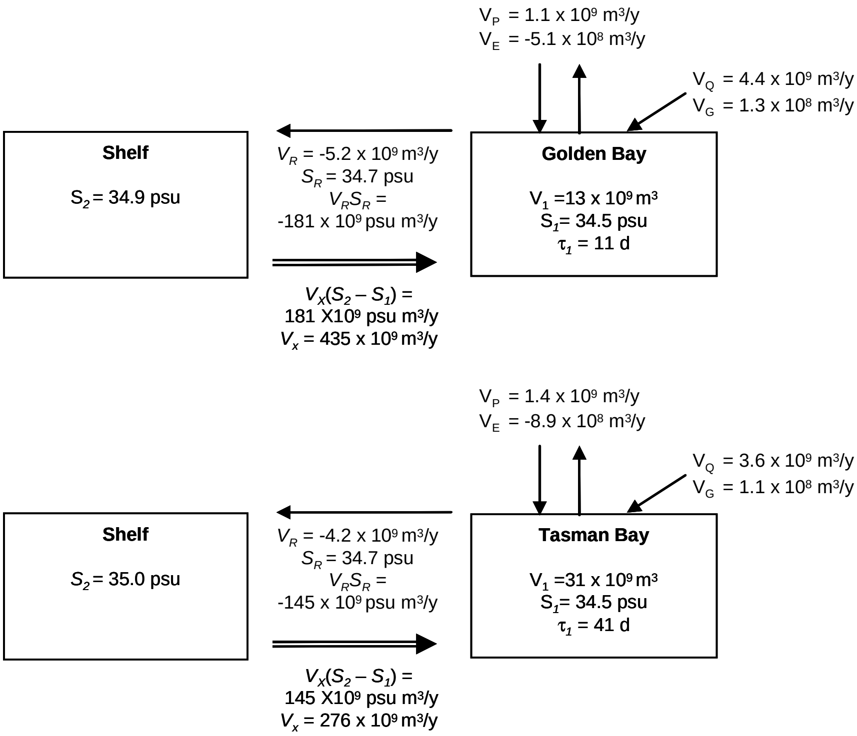

Figure 5: Water and salt budgets for Golden and Tasman Bays. Variables and subscripts are defined in the text, and arrows indicate directions and relative magnitudes of fluxes between bay and shelf systems.

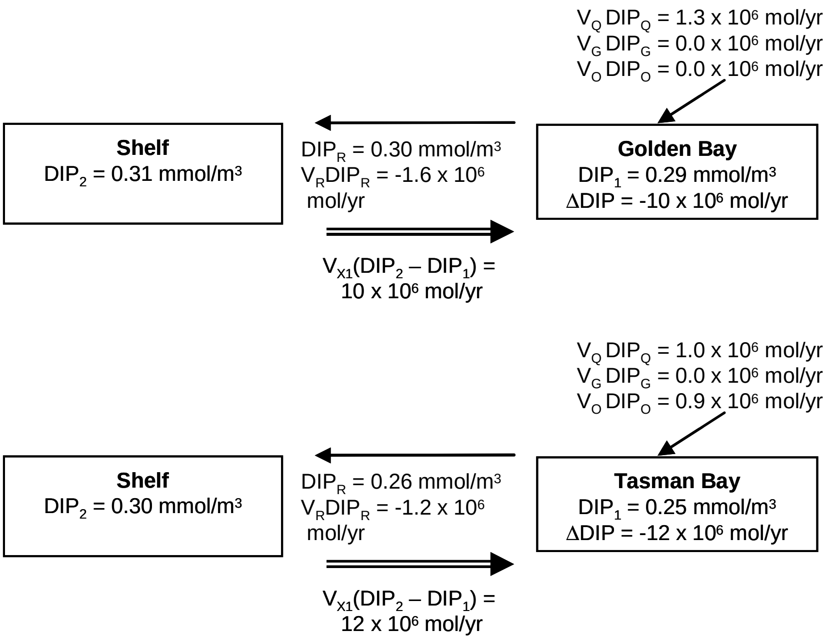

Figure 6: DIP budgets for Golden and Tasman Bays. Variables and subscripts are defined in the text, and arrows indicate directions and relative magnitudes of fluxes between bay and shelf systems.

import DIP. That is, internal system reactions are consuming DIP and producing organic matter, i.e., they are net fixing, autotrophic systems. Therefore, the differences between production and respiration (*p-r*) for the systems are apparently positive. The uptake of DIP on an areal basis is about 13 and 9 mmole DIP m^{-2} y^{-1} in Golden and Tasman Bays, respectively. If the Redfield relationship of C:P of 106:1 is assumed for these plankton-based systems (Gordon et al, 1995) they are absorbing about 1300 and 900 mmol DIC m^{-2} y^{-1}, respectively. It appears that Golden Bay is somewhat more productive than Tasman Bay.

For the non-conservative flux of DIN, ΔDIN, similar calculations apply as for ΔDIP (Figure 7). The negative values of ΔDIN indicated that Golden and Tasman Bays are net sinks for DIN. These observed values of ΔDIN were equivalent to -610 and -320 mmol m^{-2} yr^{-1} in the two systems. If DIN were absorbed in a Redfield ratio (16:1) with respect to DIP, the expected DIN fluxes (ΔDIN_{exp}) in these systems would be -200 and -140 mmol m^{-2} yr^{-1}. The discrepancies (-410 and -180 mmol m^{-2} yr^{-1}) are interpreted as the differences between net system nitrogen fixation and denitrification (*nfix-denit*), so the systems are net denitrifying, with Golden Bay being more active than Tasman Bay.

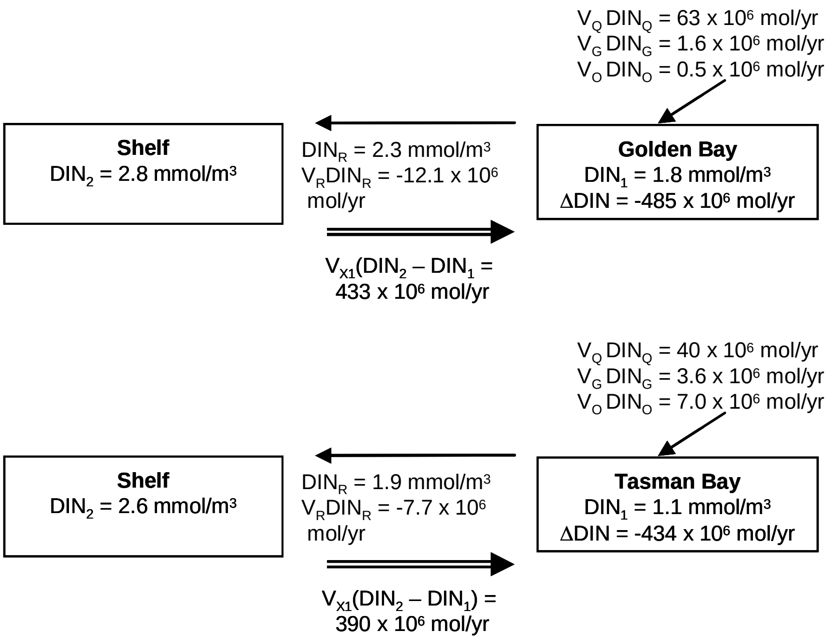

Figure 7: Same as Figure 6 except for DIN.

The (*p-r*) values for the two bays place them well within the range of autotrophic (*p-r*) estimates derived from 70 budgets in the global LOICZ budget database (Figure 8 a) compiled by Buddemeier et al. 2002). The (*nfix-denit*) values from the bays are among the lower (less denitrifying) rates tabulated by Buddemeier et al. (Figure 8 b), but are in the modal range.

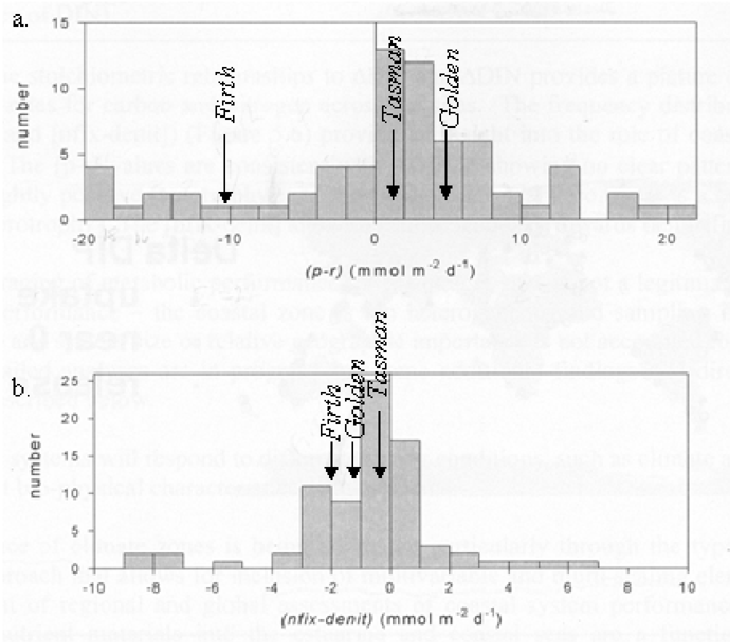

Figure 8: Histograms of values of (a) (*p-r*) and (b) (*nfix-denit*) from 70 LOICZ budgets compiled in Buddemeier et al. (2002). The values of these respective parameters for Golden and Tasman Bays are indicated as are the values for Firth of Thames and Hauraki Gulf determined by Zeldis (2005).

Non-conservative fluxes of dissolved organic P (DOP) and N (DON) were also budgeted (Figures 9, 10). It was assumed that all the riverine (DON+PON) fluxes (Table 1) were DON for these calculations. This was based on results derived from Close and Davies-Colley (1990) showing that particulate organic P (POP) in the Aorere and Motueka Rivers was <10% of the sum of DOP and POP, suggesting that organic particles were small percentages of the total organic loading to the bays. The positive values of both ΔDOP and ΔDON for Golden and Tasman Bays indicated that these systems were exporting dissolved organic matter. This is likely to have arisen from their net-autotrophic metabolism. Accounting for DON fluxes made little or no change to the net denitrification rates estimated from DIN fluxes, above (to -390 and -180 mmol N m^{-2} yr^{-1}, for each bay).

The absolute values of $\Delta DOP/\Delta DIP$ (the balance of net non-conservative export and import of DOP and DIP, respectively) were 0.74 and 0.43 for Golden and Tasman Bays, respectively. Presumably the remaining P was exported as particles. The balances for $\Delta DON/\Delta DIN$ were 0.28 and 0.21 for the two bays. The lower values of DON export percentages than that for DOP were probably due to the alternative pathway for N removal, namely denitrification.

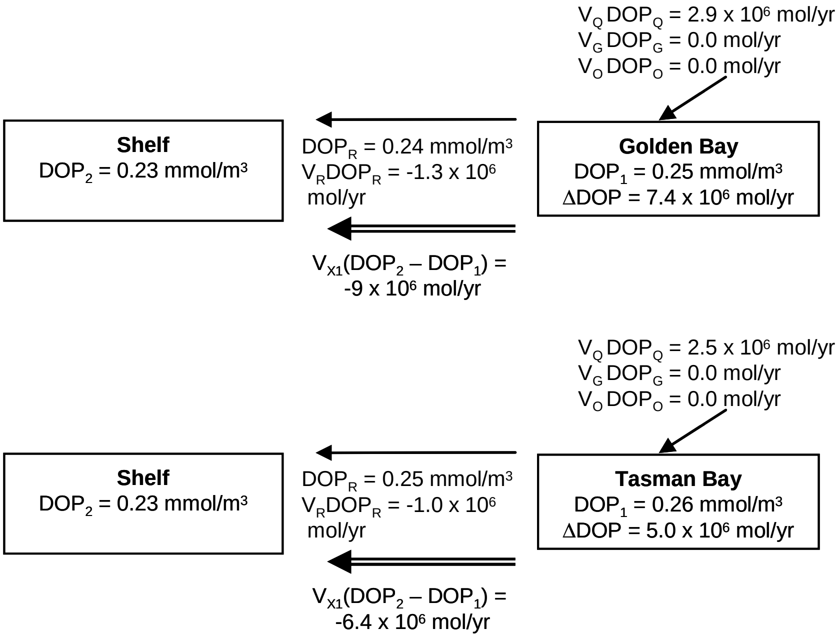

Figure 9: DOP budgets for Golden and Tasman Bays. Variables and subscripts are defined in the text, and arrows indicate directions and relative magnitudes of fluxes between bay and shelf systems.

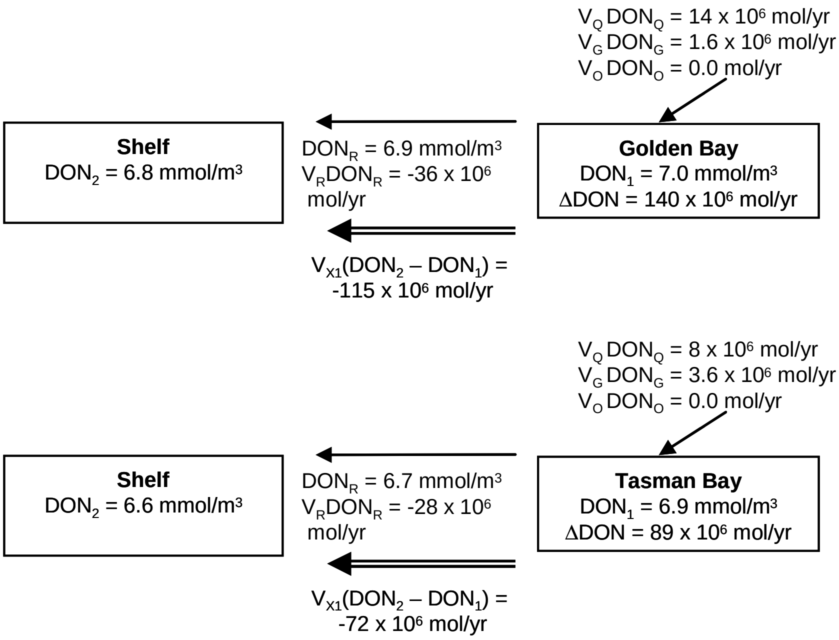

Figure 10: Same as Figure 9 except for DON.

3. Discussion

3.1. Residence times

The much shorter water residence time for Golden Bay reflects the fact that its volume was only 42% that of Tasman Bay, while its runoff and precipitation/evaporation balance were 117 and 123% that of Tasman Bay, which all lead to faster turnover. In addition, tide ranges are larger in Golden Bay than Tasman Bay, adding to the forcing terms for the stirring.

3.2. Net Ecosystem Metabolism of the bays

The bays were found to import DIP on a net basis, indicating that these systems are net-autotrophic, generating organic matter from inorganic constituents. The net export of dissolved organic matter (DOP and DON) was also evidence of this activity. Golden Bay autotrophy was more active than in Tasman Bay, consistent with higher standing stocks of chlorophyll-*a* and primary production observed there during these surveys (Zeldis and Gall 2005, Zeldis unpublished data).

The net-autotrophy in the Nelson Bays was in clear contrast with the Firth of Thames, which was strongly net-heterotrophic (Figure 8). Nitrogen loading to the Firth is dominated by riverine input relative to oceanic input (Table 2; Zeldis 2005, 2008). Firth organic N loading which emanates from the Hauraki Plains (Waikato) are more than an order of magnitude higher than those of rivers discharging to Golden and Tasman Bays (Tables 1, 2). It is likely that mineralisation of this material in the Firth drives the strong heterotrophy observed there (Table 2; Smith et al. 1991, Borges 2005). In contrast, the lack of such a catchment subsidy in Golden and Tasman Bays probably allows their net-autotrophic metabolism, which is fuelled by strong mixing of externally-mineralised inorganic nutrients into the bays from the ocean (for DIN, 6000 and 5500 t y^{-1} into Golden and Tasman Bays, respectively, *vs*. 1300 t y^{-1} into the Firth; Table 2).

Once in the bays, DIN follows two pathways. The DIP budget showed that the bay systems are net-reducing, producing organic matter from inorganic constituents. This process reduces DIN in a Redfield (~16:1) relationship with DIP. However, the net consumption of DIN by the systems (ΔDIN) exceeds that which can be ascribed solely to the net production. The remainder, (ΔDIN_{obs}-ΔDIN_{exp}), is ascribed to net-denitrification, in which DIN is reduced to N_2 gas and lost to the atmosphere.

Similar N dynamics were observed in the Firth, but with an important point of contrast with the bays in terms of the balance of N loading and dentrification. DIN import to the Firth system was insufficient to sustain its denitrification and required an oceanic PON subsidy (Table 2). In contrast, the strong DIN import to the Nelson Bays was more than sufficient to support their denitrification.

Table 2: Nelson Bays and Firth of Thames net fluxes (t y^{-1}) of dissolved inorganic and organic N from rivers and the ocean boundary (ref. Fig. 2). Positive values indicate inflows, and negative values outflows, with respect to the systems. River organic N is not split for DON and PON in the hydrometric data, and ocean PON is not estimated by the budgeting method. Also shown is the net DIC consumption (positive indicates net production) and net N loss via denitrification. Firth data were from a re-analysis of the Zeldis (2005) budget with SPARROW output for terminal river reaches (Zeldis 2008).

	River DIN	River DON+PON	Ocean DIN	Ocean DON	Net DIC consumption	Net Denitrification
Golden Bay	900	200	6000	-1600	13000	5400
Tasman Bay	600	100	5500	-1000	15000	3400
Firth of Thames	3200	3800	1300	-2300	-52000	10700

3.3. The balance of catchment and oceanic nutrient loading

The nutrient budgets of Golden and Tasman Bays provide useful comparisons among their catchment nutrient loading terms. First, it is clear that groundwater is relatively minor relative to river water in terms of bay loading (3-10% for NO_3^-), even though the aquifers have concentrated nutrients. Wastewater from STPs is a minor nutrient contributor relative to rivers (1% for NO_3^-) in Golden Bay but a larger contributor in Tasman Bay (about 14%).

A comparison of Golden and Tasman river loadings to the bays with those to the Firth of Thames (Table 1) shows that the bay rivers contribute much lower N loading than those of the Firth, even though bay river flows are greater. In Golden and Tasman Bays riverine N loads are predominately DIN (82%), most of which (90%) is NO_3^-. The Firth loads are high in organic forms (DON and PON) – about 20 x higher than from bay rivers – and DIN is only 46% of total N.

In contrast, oceanic loading of DIN to the bays (5500 - 6000 T y^{-1}) was about 4 x greater than for the Firth (~1300 T y^{-1}). This was a function of the greater DIN levels in the source waters for the bays and not due to greater mixing rates – the conservative exchanges of salt for the bays were about the same as those of the Firth.

Interesting comparisons are possible between the N fluxes from rivers and ocean sources for Golden and Tasman Bays and the Firth of Thames, using these budget calculations. For each system, the ratio of fluxes of DIN from rivers to the total riverine and oceanic flux (corrected for residual flow losses) was:

$$V_{Q1}DIN_{Q1}/\left(V_{Q1}DIN_{Q1} - V_{R1}DIN_{R1} + V_{X1}(DIN_2 - DIN_1)\right).$$

For Golden Bay, the flux of DIN from rivers contributed about 12% of the total of river, residual and ocean supply, with mixing between the bay and the shelf contributing 88%. For Tasman Bay the contribution by rivers was 9%, with the ocean contributing the remainder. Additions of groundwater and wastewater to the catchment loads made only small differences to these percentages in the bays (1-2%). This demonstrates that the ocean dominates supply of N to both Golden and Tasman Bays, in setting their nutrient stock levels and in driving their nutrient variability. In contrast, Firth rivers contribute between 47 and 72% of Firth DIN flux under shelf upwelling and downwelling scenarios, respectively, to which may be added the heavy riverine PON contributions (Table 2).

3.4. Implications for management

In this section, facets of the Nelson Bays' systems discussed above are interpreted in terms of implications for resource management.

First, the much faster water flux through Golden Bay than Tasman Bay could potentially inform issues to do with marine farm effects. There may be less likelihood of formation of persistent marine farm footprints in Golden than Tasman Bay. This proposition could be tested with dynamic circulation model studies of the bays within which marine farms are nested.

Second, the findings for relative loadings among sources (river, groundwater and STPs) may inform catchment development and wastewater management policy. Of course, there are many reasons to manage nutrient levels in groundwater and wastewater but it would appear that impact on bay-wide nutrient levels is not an important one.

Finally, significant management implications arise from the findings on river vs ocean dominance of nutrient supply to the bays and the Firth (Table 2). Pastoral catchment development has exerted strong effects on the Firth historically, suggesting it will respond to catchment management that affects marine nutrient loading. On the other hand, the present budgets demonstrate that the dominant source (~90%) of nutrient supply to Golden and Tasman Bays is mixing of DIN from the deeper waters of the outer bay and Cook Strait into the bays (see Fig. 6). Consequently under present-day loadings Golden and Tasman Bays have much less of an 'anthropogenic legacy' than the Firth, in terms of catchment nutrient loading effects on their productivity.

Rather than strongly affecting nutrient supply, the chief role of the freshwater entering the Nelson Bays may be in driving their estuarine circulation, and in affecting density stratification and turbidity and so modifying local light and nutrient availability for primary producers (Mackenzie and Adamson 2004; Zeldis and Gall 2005; Zeldis et al. 2006). Measuring this freshwater influence deserves further research.

Instantaneous primary production rate will be set by interactions of light and nutrient supplies within the bays (Cloern 1999). The maximum rates at which components of the lower pelagic food web (e.g., phytoplankton, microbes, small and large zooplankton) grow, are consumed and recycled are determined by the extent of limitation by one or other of these dominant effects on primary production rate (Boynton et al. 1982). However, the biomasses of primary and lower secondary stocks will vary in proportion to the supply of nutrient to the system (Smith al 1981, Boynton et al. 1982). Thus, in terms of flow-on effects to larger secondary consumers such as mussels and scallops, nutrient supply and the consequent effects on food density are critical. This nutrient supply is clearly dominated by oceanic processes affecting the Nelson Bays and variability in these processes will be crucial in setting their productive conditions over time-scales relevant to large secondary consumers such as shellfish. This is a clear signal that resource and industry managers should obtain improved understanding of oceanic processes in this region, to enable improved prediction of its ecosystem services.

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