

# Magnitudes of Natural and Mussel Farm-Derived Fluxes of Carbon and Nitrogen in the Firth of Thames

Prepared by:  
John Zeldis NIWA

For:  
Environment Waikato  
PO Box 4010  
HAMILTON EAST

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National Institute of Water & Atmospheric Research Ltd  
10 Kyle Street, Riccarton, Christchurch  
P O Box 8602, Christchurch, New Zealand  
Phone +64-3-348 8987, Fax +64-3-348 5548  
[www.niwa.co.nz](http://www.niwa.co.nz)

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*Reviewed by:*



Niall Broekhuizen

*Approved for release by:*



Barry Biggs

## Executive Summary

The eastern Firth of Thames supports the largest single block of mussel farms in New Zealand, within the Wilson Bay Marine Farming Zone (WBMFZ). In addition to this development in the eastern Firth, another AMA, approximately twice the size of the WBMFZ, is under consideration by Auckland Regional Council in the western Firth. The scale of these developments has made it incumbent on EW and ARC to assess and predict environmental performance of Firth aquaculture at Firth-wide, as well as local AMA scales.

This study reports new research investigating Firth-wide ecosystem effects which could result from increasing intensities of existing and proposed AMA development. It uses marine and terrestrial hydrographic information to evaluate fundamental ecosystem processes at the scale of the Firth: incorporation of carbon and nitrogen into organic material through system import and primary production, and losses of nitrogen and carbon through system denitrification, respiration and export. These values are compared with carbon and nitrogen assimilation and respiration by mussel farms, at the various AMA development intensities. The intention of the work is to provide perspectives on the relative magnitudes of ecosystem and farm processes, under the various intensities of AMA development.

The work combines information from three sources. The first was a water, salt and nutrient mass-balance budget for the Hauraki Gulf and adjacent Firth of Thames systems. The budget was based on field samples collected over four seasonal NIWA voyages in the Gulf and Firth region in 2000-01, and calculated the non-conservative flows, sources and sinks of carbon and nutrients through the systems, after correcting for the conservative flows and mixing of water and salt. The second was an estimate of Firth primary productivity, i.e., carbon fixation rate, determined over the Firth using two sets of seasonal voyages made in 1998-2000 and 2002-2003. The third data source described mussel respiration rate and elemental composition determined within NIWA Aquaculture Sustainability programme research.

Important outcomes from the mass balance budget and primary production experiments were:

- Mean water residence time of the Firth system was 12 days, implying a high degree of internal horizontal exchange in the Firth.
- Strong non-conservative flux of dissolved inorganic phosphorus (DIP) from the Firth to the Gulf reflected the net decomposition of organic matter to inorganic nutrients, and the net production of dissolved inorganic carbon (DIC) by the Firth. Thus, for the Firth, respiration ( $r$ ) of organic matter was faster than primary production ( $p$ ) of organic matter, and  $p-r$ , or net ecosystem metabolism, was negative ( $-12 \text{ mmol C m}^{-2}\text{d}^{-1}$ ).

- This excess of oxidation over production must be subsidised by net import of substantial amounts of labile particulate organic carbon (POC) from the land and offshore, and its oxidation in the Firth. The required net POC import was estimated to be about 54 700 tC y<sup>-1</sup>.
- The annual mean primary production estimate was 38 mmol C m<sup>-2</sup> d<sup>-1</sup> (or 168 g C m<sup>-2</sup> y<sup>-1</sup>). Because  $p-r$  was -12 mmol C m<sup>-2</sup> d<sup>-1</sup>, Firth respiration ( $r$ ) was 38 +12 = 50 mmol C m<sup>-2</sup> d<sup>-1</sup>.
- Deviations of the observed and expected fluxes of dissolved inorganic nitrogen (DIN), based on stoichiometry with DIP flux, indicated that the Firth denitrifies large amounts of fixed nitrogen to nitrogen gas on a net basis (1.9 mmol m<sup>-2</sup> d<sup>-1</sup>). This capacity for denitrification buffers the Firth against excessive N loading from terrestrial and marine sources, which could otherwise cause eutrophication. The denitrification, like organic matter oxidation, was subsidised by substantial imports of labile particulate organic nitrogen (PON: estimated as 9300 tN y<sup>-1</sup>).
- The denitrification flux was about one-third the size of the primary production N flux. This suggests that N, once introduced into the Firth by net DIN or PON import, cycles about three times through the production-decomposition cycle, on average, before being lost to denitrification. Thus, recycling underpins the large amount of primary production found within the Firth, by ‘amplifying’ the imported N. It also indicated that most (about 73%) of the phytoplankton and detrital PON within the Firth at any one time is derived from primary production regenerated *in situ*, rather than from newly-introduced phytoplankton or PON from the Gulf or rivers.

These results on Firth system primary production, respiration and denitrification were compared with information on mussel biomass, C and N composition, and weight-specific respiration, to draw conclusions about the importance of mussel aquaculture within the Firth ecosystem. At the present level of AMA development, mussel biomass harvest removes 0.2% of Firth C primary production y<sup>-1</sup>. At projected biomasses of maximum AMA development (= WBMFZ fully developed + Western Firth AMA) the harvest would remove 1.6% of primary production y<sup>-1</sup>. For these respective scenarios, mussel C respiration would account for 0.3 and 1.8% of present Firth system respiration. Similar to denitrification, the mussel harvest represents a net sink for nitrogen, removing nitrogen from the internal cycle supporting Firth primary production. At maximum AMA development, about 1.4% of Firth N primary production (i.e., DIN fixed) would be removed by the mussel harvest. This is about 2.8% of the size of the denitrification sink.

These calculations give perspectives on the significance of carbon and nitrogen removal by the mussels, relative to the amount of these materials currently supplied to the Firth, which sustain its primary productivity, respiration and denitrification.

The estimates of Firth system primary production, respiration and denitrification were shown to be reasonable in comparison with other studies of temperate coastal regions, including the Hauraki Gulf and Firth of Thames. They will be compared in upcoming research with datasets currently under analysis for the Firth system, derived from field surveys and experiments. The coefficient of variation of the primary production estimate was 28% and those of respiration and denitrification to be 24%.

The current and projected effects of AMA development were compared with the current water column Limits of Acceptable Change (LAC) criterion that chl-*a* depletion should not exceed 20% over 10% of the Firth. The results indicate that biomass would be reduced by 5% over 10% of the Firth, at WBMFZ fully developed, assuming a linear relationship between phytoplankton production and biomass. It also suggests that at development levels approaching WBMFZ fully developed and Western Firth AMA fully developed, biomass would be reduced by 16% over 10% of the Firth. Both these levels are less than the LAC criterion. Considering the levels of precision in the estimates, it appears that at maximum development the LAC criterion may be approached.

These conclusions may be compared with those of the biological modelling of Firth aquaculture by Broekhuizen et al. (in prep), who found that: ‘simulations indicate that if farming expands to the extent implied by pending applications (i.e., 3 x WBMFZ), the 20% / 10% threshold will be approached, and perhaps exceeded from time to time, but probably not when averaged over longer periods’. These two entirely independent approaches have thus yielded a similar result with respect to the overall Firth system. That is, it is unlikely that phytoplankton depletion in the Firth will approach the current LAC criterion, until AMA development expands to the extent implied by pending applications.

## 1. Introduction

The eastern Firth of Thames supports the largest single block of mussel farms (for New Zealand green mussel, *Perna canaliculus*) in New Zealand, within the Wilson Bay Marine Farming Zone (WBMFZ). Environment Waikato administers this AMA, and has overseen a comprehensive programme of monitoring (funded by the Group A consortium of Wilson Bay farmers and provided by NIWA) to measure the environmental performance of this development (Wilson Bay Consortium (Group A) and NIWA 2001). Water quality, benthos and hydrodynamics have been monitored, to determine if significant environmental effects have resulted from aquaculture. In early 2004 Group A were cleared to develop the first part of this staged development (Area A) to its full 470 farmed ha extent (additional to a pre-existing adjacent area of 220 farmed ha). Area B of the WBMFZ, if developed, will further expand this farmed area to 1200 hectares. In addition to the development in the eastern Firth, another AMA, approximately twice the size of the WBMFZ, is under consideration by Auckland Regional Council in its conservancy in the western Firth. Were all these developments eventually to reach their maximum size, an area of about 3600 farmed ha, or 3.3% of the surface area of the Firth, would be occupied by mussel farms.

The scale of these developments has made it incumbent on EW and ARC to assess and predict environmental performance of Firth aquaculture at Firth-wide, as well as local AMA scales, because of the importance of maintaining the Firth as a healthy ecological entity (NIWA 2003). Accordingly, EW, ARC, the Group A consortium and NIWA have collaborated on a number of initiatives to monitor and predict Firth-wide aquaculture effects of the WBMFZ and proposed Western Firth AMA, including the Firth of Thames sustainability modelling of Broekhuizen et al. (2004). A management framework has also been instituted, based on the Limits of Acceptable Change (LAC) concept, to manage environmental performance of aquaculture at these scales (Turner and Felsing 2005).

The present report describes new research investigating Firth-wide ecosystem effects, which could result from increasing intensities of existing and proposed AMA development. The work uses marine and terrestrial hydrographic information to evaluate fundamental ecosystem processes at the scale of the Firth: incorporation of carbon and nitrogen into organic material through system import and primary production, and losses of nitrogen and carbon through system denitrification, respiration and export. These values are compared with carbon and nitrogen assimilation and respiration by mussel farms, at the various AMA development intensities. The intention of the work is to provide perspectives on the relative magnitudes of ecosystem and farm processes, under the various intensities of AMA



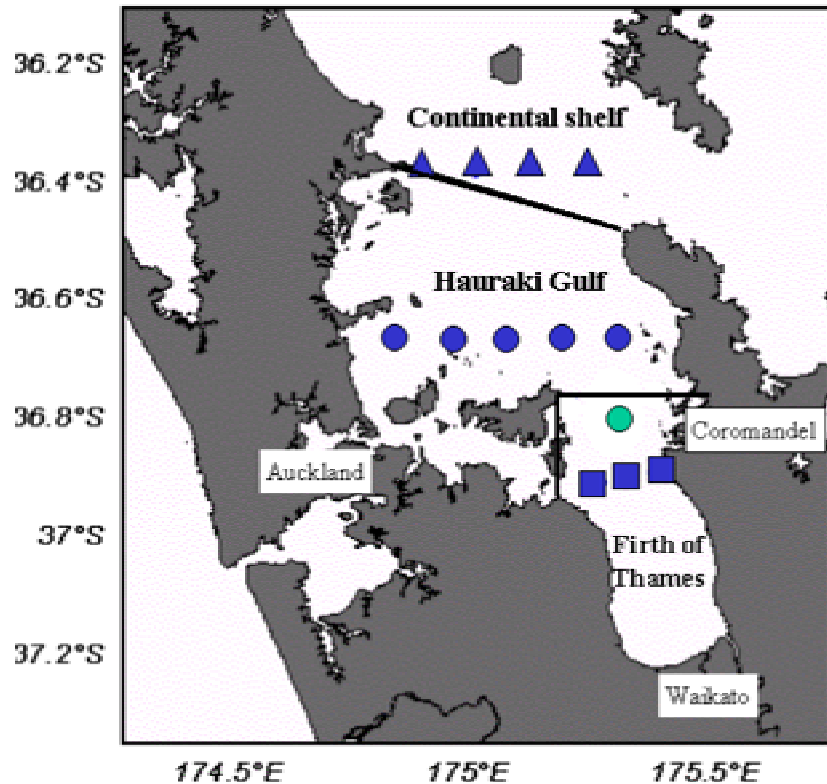
development, to inform Council decision-making about sustainability of mussel farming in the region, now and in future.

The work combines information from three sources, described in more detail in the Methods section. This first is a water, salt and nutrient mass-balance budget for the Hauraki Gulf and adjacent Firth of Thames (Zeldis 2004 in press), based on hydrographic samples obtained in 2001-2002 and protocols developed within the 'Land-Ocean Interactions in the Coastal Zone' (LOICZ) programme of the International Geosphere-Biosphere Programme (Gordon et al. 1996). The purpose of the budget was to calculate the flows, sources and sinks of biologically active, 'non-conservative' materials (carbon, nutrients) through the Firth, Hauraki Gulf and adjacent shelf systems, derived after correcting for the flows and mixing of 'conservative' materials (water, salt) through the systems. The second data source was an estimate of Firth primary productivity, i.e., carbon fixation rate, determined for Firth of Thames waters using data from series of voyages in 1999-2000 and 2002-2003 (Gall et al. 2002; Zeldis 2003; author's unpubl. information). This information was collected separately from the budget data, but was nevertheless essential for budgetary interpretation. The third data source describes mussel respiration rate and elemental composition (Ren and Ross 2005; J. Ren, NIWA, pers. comm). The combination of these three data sources has allowed evaluation of the potential influence of mussel farms on Firth system carbon and nitrogen fluxes.

## 2. Method

### 2.1. Overview of budgetary approach

The budgetary approach uses a class of mass balance budgets known as "stoichiometrically linked water-salt-nutrient budgets" (Gordon et al. 1996). The nutrients of specific interest here are carbon (C), nitrogen (N) and phosphorus (P). The budget was based on salinity and nutrient samples collected in quarterly oceanographic surveys on the continental shelf outside the Hauraki Gulf, and within the Hauraki Gulf and Firth of Thames (Zeldis 2004; Fig. 1), obtained within the Cross-shelf Exchange (C-SEX) project of the NIWA Oceans Ecosystems Programme. The work was an extension of a previous Hauraki Gulf budget analysis, based on samples collected in 1996-97 (Zeldis and Smith 1999). Details of the sampling and budget methods and results are given in the Appendix; below I give a general overview of the budgetary approach. This is followed by a description of the outcomes for the Firth, and then how these outcomes were interpreted in the present investigation of aquaculture effects.



**Figure 1:** Place names, sampling stations and system boundaries used in Zeldis (2004). Shelf stations are triangles, Gulf stations are circles and Firth stations are squares. The shelf and Gulf stations are the same as used in the 1999 LOICZ budget (Zeldis and Smith 1999). See the Appendix for details. The green circle is the Firth of Thames mooring site.

The method comprises a series of budgets which are solved in a prescribed order (after Gordon et al. 1996).

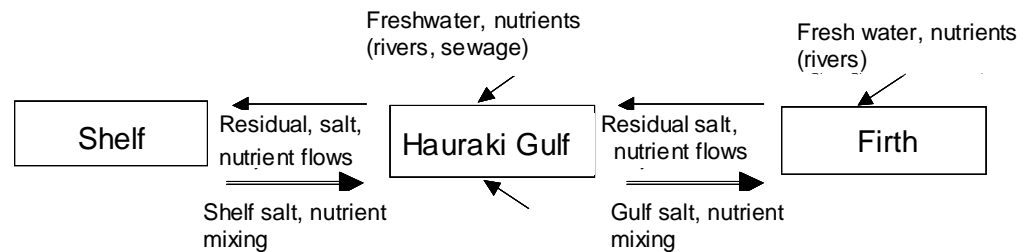
### 2.1.1. Water budget

A budget is established of freshwater flows with respect to the Firth system (river runoff, precipitation, groundwater, sewage and evaporation). There must be compensating outflow to the adjacent system, i.e., the Gulf, to balance the water volume in the Firth system. This is the ‘residual’ flow (Figs. 2, Appendix Fig. 4).

### 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 Firth by the residual flow to the Gulf must be replaced by mixing between the Gulf and the Firth, to sustain the salinity difference

observed between the two systems (Figs. 2, Appendix Fig. 4). The water and salt budgets describe the exchange of water between the Firth and Gulf systems by the processes of advection and mixing. The validity of the assumption of steady state incorporated in this budget is discussed in the Appendix.



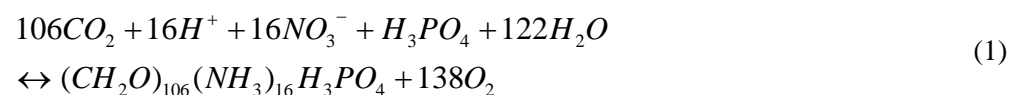
**Figure 2:** Schematic diagram of system boxes used in LOICZ budget of Zeldis (2004). Main flows of freshwater, salt and nutrients are indicated (For details see the Appendix).

### 2.1.3. Budgets of non-conservative nutrients

Dissolved materials (C, N, P) will exchange between the Firth and Gulf systems due to the residual and mixing flows described above. Deviations of material concentrations from predictions based on the previous steps are quantitatively attributed to net non-conservative reactions of materials in the system (Fig. 2, Appendix Figs. 5, 6).

### 2.1.4. Stoichiometric relationships among non-conservative budgets

Net ecosystem metabolism is typically measured as the balance between net primary production of organic material and its decomposition, as represented by an equation of the form:

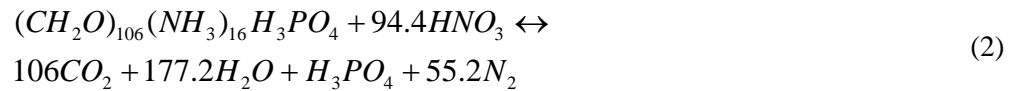


This equation shows the relationships among C, N, P and oxygen typical of 'Redfield' molar ratios, for organic material found throughout much of the world ocean (with slight modification, such an equation can be written with  $NH_4^+$  instead of  $NO_3^-$  as the nitrogen source, but the stoichiometry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

It should be noted from the equation that C has a major gas phase, namely  $CO_2$  gas exchange across the air-sea interface. This means that net ecosystem metabolism as

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

Nitrogen also has major flux pathways involving the gas phase during denitrification and its back-reaction, N fixation:



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 C:N:P composition ratios of reactive organic particles as shown in the equation above. The deviation of the *observed* (i.e., budgeted) fluxes of DIN from that *expected* (based on DIP flux) provides an estimate of net denitrification. In the current application the commonly found Redfield molar values for C:N:P of 106:16:1 were used, on the assumption that most organic matter metabolised in the system is of marine planktonic origin (see Discussion).

## 2.2. Primary production

Depth-integrated primary productivity of Firth of Thames waters were determined using a depth-integrated model approach of Behrenfeld and Falkowski (1997):

$$\sum PP = P_{opt}^b \times f[E_0] \times DL \times C_{avg} \times Z_{eu},$$

where the optimum chlorophyll-specific carbon fixation rate of the productivity profile,  $P_{opt}^b$  (mg C mg chl<sup>-1</sup> h<sup>-1</sup>), is combined with a non-linear irradiance dependent function ( $f[E_0]$ , dimensionless), daylength ( $DL$ , h), average water column chl- $a$  ( $C_{avg}$ ) and euphotic zone depth ( $Z_{eu}$ ) to calculate integrated production ( $\sum PP$ , mg C m<sup>-2</sup> day<sup>-1</sup>). In the present application,  $P_{opt}^b$  data were obtained from photosynthesis-irradiance determinations (Gall et al. 1999) made on board ship during primary production experiments over 6 C-SEX voyages from spring 1999 to summer 2000 at the Firth of Thames mooring site (Fig. 1; Gall et al. 2002). The  $P_{opt}^b$  results from spring 1999 and 2000 were averaged, as were those from summer 1999 and 2000, and

these means were then averaged with the autumn and winter 2000 values, to produce an annual mean. The parameter  $f[E_0]$  was from Behrenfeld and Falkowski (1997).  $C_{avg}$  was water-column average chl-*a* determined over water column profiles ( $n = 10$  to 17 profiles per voyage; each profile with 2 to 6 chl-*a* values, depending on bottom depth), sampled over a grid pattern from inner to outer Firth waters in summer 2002, and autumn, winter, spring, and summer 2003, in C-SEX research (e.g., Zeldis 2003).  $Z_{eu}$  was penetration of light in these water columns to the depth of 1% of its surface value, determined using a log-linear fitting routine to the attenuation of photosynthetically active radiation from these CTD profiles (author's unpublished data). The mean  $\Sigma PP$  value from the two summer voyages was averaged with the other seasonal values to calculate the annual mean  $\Sigma PP$ .

### 2.3. Mussel elemental composition and respiration

Elemental composition and respiratory values were determined for *Perna canaliculus* as described below.

1. Mussel green weight (GW):total dry weight (tDW), where GW is live weight and tDW is the sum of shell weight plus meat dry weight (DW) (J. Ren NIWA, pers. comm.). It was assumed that shell GW = shell DW;
2. Meat (including gonad) dry weight (mDW) as a proportion of tDW was determined from unpublished data of Hayden (B. Hayden, NIWA pers. comm);
3. Meat C (mC) and meat N (mN) as proportions of mDW were determined from Ren and Ross (2005) and unpublished data of Ren (J. Ren NIWA, 2005);
4. Shell C (sC) and shell N (sN) as proportions of shell DW (taken as equal to shell GW) were determined from C and N analyses of horse mussel *Atrina zelandica* shells (Gibbs et al. 2005), on the assumption that these ratios are similar to those of *P. canaliculus*;
5. Percentage C respired as a percentage of mC, for an 80 mm shell length mussel, was provided by Ren (J. Ren, NIWA pers. comm.).

### 2.4. Scenario designation

The mussel annual GW harvest biomasses of the various existing and projected scenarios investigated in this study were defined as follows.

- *Scenario 1: Nominal Area A stage 1 plus the existing area.* This constitutes a total GW harvest biomass of approximately 9000 t<sup>1</sup>;
- *Scenario 2: Area A fully developed (stages 1 and 2) plus the existing area.* Taken as two times stage 1 biomass, plus the existing area, for a total GW harvest biomass of 13000 t;
- *Scenario 3: WBMFZ fully developed.* Taken as two times Area A fully developed plus existing area, for a total GW harvest biomass of 21000 t;
- *Scenario 4: Two times WBMFZ.* Taken to emulate WBMFZ plus part development of Western Firth AMA, for a total GW harvest biomass of 42000 t;
- *Scenario 5: Three times WBMFZ.* Taken to emulate WBMFZ plus full development of Western Firth AMA for a total GW harvest biomass of 63000 t.

It was assumed that the mussel growth period was one year, from seeding to harvest, in these calculations (J. Wilson, Sealord, pers. comm.).

### 3. Results and Discussion

#### 3.1. Carbon and nitrogen fluxes

##### 3.1.1. Budget outcomes

The LOICZ budget was implemented as an annual average of 96, 108 and 50 samples taken at shelf, Gulf and Firth system sampling sites (Fig. 1), divided nearly equally between four NIWA seasonal surveys made in September, November, March and July 2000-01. It was also implemented as a spatial average, with all samples in each system averaged in vertical and horizontal dimensions. Thus, the outcomes for the Firth are not temporally or spatially resolved, unlike in dynamic models such as that of Broekhuizen et al. (2004). Sensitivity analyses of various temporal and spatial averaging schemes on idealised LOICZ budgets made by Webster et al. (1999; discussed in the Appendix), indicate that these averaging assumptions were unlikely to

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<sup>1</sup> Note: this biomass approximates, but does not represent an actual harvest value, because of commercial sensitivity.

introduce significant bias in estimated flows of conservative and non-conservative materials. Accuracy and precision of budget outcomes are described in the Discussion.

Important budget outcomes were:

1. Mean water residence time of the Firth system, or the average time required for the summed residual and mixing flows to exchange the water volume of the Firth with the Gulf, was 12 days. The exchange time of the combined Gulf and Firth systems with the shelf was 58 days. The shallowness of the Firth and its exposure to the Gulf ensure that its turnover is fairly rapid. This implies a high (but unresolved) degree of internal horizontal exchange within the Firth.
2. Descriptions of the oceanic and terrestrial dissolved inorganic and organic nutrient fluxes to the Firth and Gulf were made by the budget (Appendix Figs. 5, 6). River and groundwater flows provided a ‘basal level’ of inorganic nutrient supply, whilst upwelling and downwelling offshore over the shelf generated most of the supply variation. Fluxes of DIP and DIN were highly non-conservative, indicating strong internal processing. Dissolved organic phosphorus (DOP) and nitrogen (DON) were more abundant in river, Firth and Gulf waters than DIP and DIN, but their non-conservative fluxes between systems were small relative to their standing stocks, showing their more conservative transport and refractory nature, and consequently small effects on denitrification calculations. Particulate organic carbon (POC) and nitrogen (PON) supplies and fluxes are not explicitly determined in the budget because of inherent imprecision in their estimation (see Gordon et al. 1996 for further discussion). However, as will be seen below, these can be inferred from budget results, and they are substantial and important.
3. The strong non-conservative flux of DIP from the Firth to the Gulf and from the Gulf to the shelf (Fig. Appendix 5a) was interpreted as reflecting the net decomposition of organic matter to inorganic nutrients, and the evolution of dissolved inorganic carbon (DIC) according to equation 1. Thus, for the Firth and Gulf, respiration ( $r$ ) of organic matter was faster than primary production ( $p$ ) of organic matter. Thus,  $p-r$ , or net ecosystem metabolism, was negative.
4. For the Firth,  $p-r$  was  $-12 \text{ mmol C m}^{-2} \text{ d}^{-1}$ . This excess of oxidation over production must be subsidised by net import of substantial amounts of labile organic carbon from the land and offshore, and its oxidation in the Firth *in situ*. This import is likely to be in the form of POC rather than dissolved organic carbon (DOC), as evidenced by the small net flux of DOP (and hence

DOC). The required net POC import was estimated as  $4.6 \times 10^{12}$  mmol C  $y^{-1}$  ( $\sim 54\,700$  tC  $y^{-1}$ ).

5. Because system respiration exceeded system primary production (see next section) by  $12$  mmol C  $m^{-2} d^{-1}$ , gross Firth respiration ( $r$ ) was  $38 + 12 = 50$  mmol C  $m^{-2} d^{-1}$ .
6. The deviations of the observed and expected fluxes of DIN in the Firth and Gulf indicated that these systems denitrify large amounts of nitrogen gas to the atmosphere on a net basis, according to equation 2 (estimated as  $1.9$  mmol  $m^{-2} d^{-1}$  for the Firth). This capacity for denitrification buffers the Firth and Gulf systems against excessive N loading from terrestrial and marine sources, which could otherwise cause eutrophication.
7. Denitrification occurs largely in the benthos and, like organic matter oxidation, was subsidised by substantial imports of labile PON. The amount of PON required to balance the dissolved fluxes of DIN and DON and the denitrification flux, was estimated as  $6.6 \times 10^{11}$  mmol N  $y^{-1}$  ( $\sim 9300$  tN  $y^{-1}$ ). DIN inputs to the Firth account for about 38% of the denitrification flux.

### 3.1.2. Primary biomass and production

The mean production value was  $460$  mg C  $m^{-2} d^{-1}$  ( $38$  mmol C  $m^{-2} d^{-1}$  or  $168$  g C  $m^{-2} y^{-1}$ ; Table 1). Mean column-averaged chl-*a* was  $20.9$  mg chl-*a*  $m^{-2}$ . Precision for these estimates is determined in the Discussion.

### 3.1.3. Mussel elemental composition and respiration

Estimates for mussel elemental composition and respiration are shown in Table 2. It should be noted that meat C and N content is much higher than C and N content of the shell. This is important, because tDW is dominated by shell weight. Thus, most of mussel GW is contributed by a component (the shell) that has very low organic C and N content.



**Table 1:** Water-column average primary production ( $\Sigma PP$ :  $\text{mg C m}^{-2} \text{ d}^{-1}$ ) and water-column average chl-*a* to the 1% light level ( $\text{mg chl-}a \text{ m}^{-2}$ ) in the Firth of Thames measured over 5 seasonal voyages in 2002-2003. Also given are the average values for annual periods covered by the voyages (see text), and their coefficients of variation (CVs; see discussion).

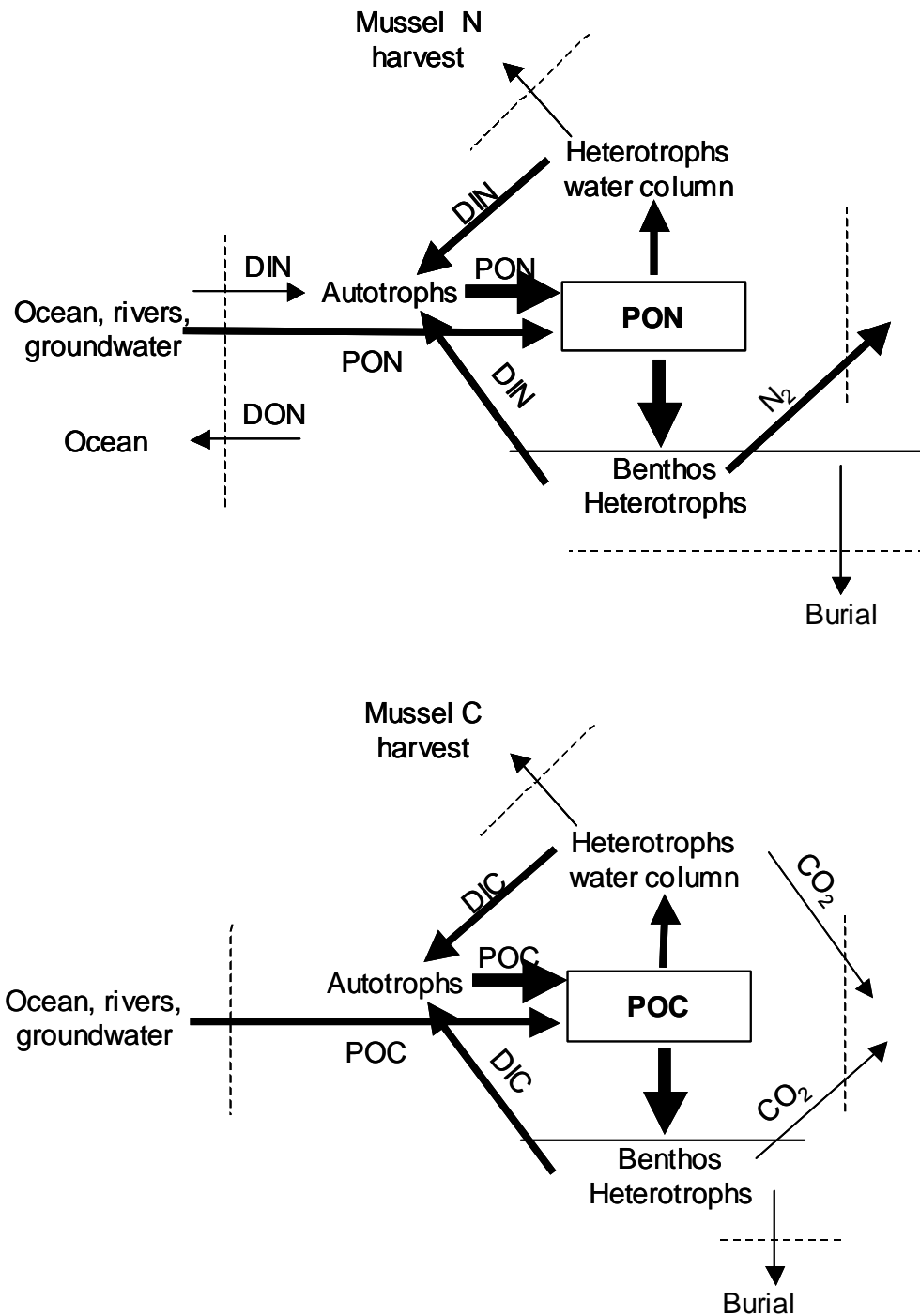
Season	Avg $\Sigma PP$	Avg chl- <i>a</i> 1%
Summer 2002	570	21.0
Autumn 2003	359	16.7
Winter 2003	190	11.7
Spring 2003	362	18.7
Summer 2003	1053	38.8
mean	460	20.8
CV	0.28	0.09

**Table 2:** Elemental composition and respiratory data for *Perna canaliculus* used in this study. GW: mussel green (live) weight; tDW: total dry weight (sum of shell weight plus meat DW); mDW: meat (including gonad) DW; mC: meat C weight; mN: meat N weight.

Item	Value
GW: tDW	1.70
mDW: tDW	0.12
mC:mDW	0.41
mN:mDW	0.07
sC:sDW	0.013
sN:sDW	0.002
C respired: mC	0.005

### 3.2. Assessing influence of aquaculture

Results on Firth system primary production, respiration and denitrification, combined with mussel composition and respiration information, allow conclusions to be made about the importance of mussel aquaculture within the Firth ecosystem. To understand relationships of these processes, it is useful to posit conceptual models for nitrogen and carbon cycling that put them into context (Fig. 3).



**Figure 3:** Nitrogen and carbon net fluxes and internal cycling in the Firth of Thames system. Dashed lines are system boundaries. Increasing arrow thicknesses denote small, medium and large flows. ‘Autotrophs’ are all primary producers and ‘Heterotrophs’ are all secondary producers including mussels.

The N model shows the major fluxes of N, between the loading of PON and DIN to the system, uptake of the new DIN by autotrophs in primary production, decomposition of PON by heterotrophs (including mussels) to DIN, and recycling of the DIN *via* autotrophs to PON. Competing with the internal production:decomposition cycle is the major N<sub>2</sub> sink through denitrification and a smaller burial sink. Also competing with the internal primary production cycle is the removal of nitrogen by the production and harvest of mussels. Carbon cycling has similar dynamics, centred on POC, with recycled production of DIC, including its major sink to the atmosphere as CO<sub>2</sub>. The DIC production is Firth system respiration, produced by all biota including mussels. This heterotrophy remineralises nutrients, including DIN, driving the production cycle and supplying DIN to the denitrification sink. Carbon is also removed by the mussel harvest. The absolute and relative sizes of some of these net fluxes are given in Table 3, which is a compendium of rates derived and discussed in the Appendix, converted to common units of tonnes y<sup>-1</sup>.

The analysis (Table 3) shows the large production and respiration fluxes that the Firth system supports. The denitrification flux is about one-third the size of the primary production N flux. This suggests that N, once introduced into the Firth by net DIN or PON import, cycles about three times through the production-decomposition cycle on average, before being lost to denitrification (Fig. 3). This demonstrates how recycling generates the large amount of primary production found within the Firth, by ‘amplifying’ the imported N. It also indicates that most (~72%) of the phytoplankton and detrital PON in the system at any one time in the Firth is derived from primary production regenerated *in situ*, rather than from newly-introduced phytoplankton or PON from the Gulf or rivers.

**Table 3: Absolute and relative sizes of primary production, respiration and denitrification fluxes in the Firth for C and N, derived from primary production and budgetary analyses.**

Item	Value
Firth C primary production (tC y <sup>-1</sup> )	184000
Firth N primary production (tN y <sup>-1</sup> )	28000
Firth C respiration (tC y <sup>-1</sup> )	238000
Firth denitrification (tN y <sup>-1</sup> )	10600
Firth denitrification: Firth N primary production	0.38

The carbon fluxes can be used to assess aquaculture effects within the Firth system. First, Firth primary production (carbon fixation rate) can be compared with the Wilson Bay mussel carbon production extracted through harvest (from elemental composition and mussel production rate information). This latter proportion includes the C

removed within the mussel production plus the C respired in the CO<sub>2</sub> flux from the mussels<sup>2</sup>, and allows comparison of the magnitude of carbon requirements for mussel production, relative to the ability of the Firth to supply fixed C to the whole system. We can also compare the total DIC respiration by the mussel biomass with the total Firth system DIC respiration, to give a perspective on the relative importance of mussel metabolism with respect to the metabolism of the whole system. Finally, we can use the N fluxes, to compare the extraction of N by the harvest with the limitation imposed on system productivity by the denitrification flux.

The results (Table 4) show that, at the present level of AMA development (Scenario 1), mussel C losses remove 0.2% of Firth C primary production per year. At projected biomasses of Scenario 5 (maximum AMA development) these losses would remove 1.6%. For scenarios 1 and 5, mussel C respiration would account for 0.3 and 1.8% of present Firth respiration, respectively.

**Table 4: Mussel farm fluxes compared to Firth fluxes, for various AMA scenarios. Scenarios and corresponding annual green weight annual harvest tonnages are for: (1) Nominal Area A Stage 1 plus existing; (2) Area A fully developed plus existing; (3) Area A and B plus existing (i.e., WBMFZ fully developed); (4) WBMFZ fully developed x 2; (5) WBMFZ fully developed x 3.**

Scenario	1	2	3	4	5
Tonnage (GW)	9000	13000	21000	42000	63000
Mussel C production:Firth C primary production	0.002	0.003	0.005	0.011	0.016
Mussel C respiration:Firth C respiration	0.003	0.004	0.006	0.012	0.018
Mussel N production:Firth N primary production	0.002	0.003	0.005	0.009	0.014
Mussel N production:Firth denitrification	0.004	0.006	0.009	0.019	0.028

Mussels also assimilate nitrogen, and when the mussels are harvested, it is removed from the system (cf. Fig. 3). Thus, similar to denitrification, the harvest represents a net sink for nitrogen, removing nitrogen from the internal cycle supporting Firth primary production. The third row of Table 4 shows that about 1.4% of Firth N primary production (i.e., DIN fixed) would be removed by the mussel harvest at maximum development.

Because Firth primary production is constrained by nitrogen supply (Broekhuizen et al. 2003, Chang et al. 2003; Zeldis 2004), it is important to determine to what extent nitrogen removal through mussel assimilation would contribute to that limitation. The

<sup>2</sup> The CO<sub>2</sub> flux from the mussels was calculated using the ratio of net to gross system respiration from the budget (12:50 mmol C m<sup>-2</sup> d<sup>-1</sup>), on the assumption that this represented the CO<sub>2</sub> to DIC flux ratio for all heterotrophs including mussels.

final row of Table 4 indicates the size of this effect, relative to the denitrification. At maximum development (Scenario 5), the size of the harvest N sink is about 2.8% of size of the denitrification sink.

These calculations give perspectives on the significance of carbon and nitrogen removal by the mussels, relative to the amount of these materials currently supplied to the Firth, which sustain its primary productivity, respiration and denitrification.

### 3.3. Accuracy and precision

Before considering the implications of these findings for aquaculture within the Firth ecosystem, it is important to consider their accuracy and precision. Clearly, the estimate of primary production of the Firth is central to the findings. The annually averaged primary productivity value of  $168 \text{ g C m}^{-2} \text{ y}^{-1}$  assessed from the seasonal surveys across the Firth of Thames is well within a range of typical productivity values for temperate coastal waters compiled by S. Bury (NIWA, pers. comm.) for shelf and coastal areas in Hauraki Gulf and overseas. Precision of the  $\Sigma PP$  estimate was determined using a ‘bootstrap’ approach by generating 100 normally-distributed estimates of  $f [E_0] \times DL \times C_{avg} \times Z_{eu}$  from the mean and standard errors of this product across the 2002-2003 voyages, and multiplying them by 100 estimates of  $P_{opt}^b$ , generated from the mean and standard error of this parameter from the 1999-2000 voyages. The standard deviation of the resulting 100 products was taken as the CV of  $\Sigma PP$  and was 0.28 (Table 1). The mean of values of column - averaged chl-*a* from the 2002-2003 surveys had CV of 0.09.

For the elements of the LOICZ budget, it is noted that gross Firth respiration ( $r$ :  $50 \text{ mmol C m}^{-2} \text{ d}^{-1}$ ) was within the range for a number of European estuaries documented by Frankignoulle et al. (1998), while net metabolism ( $p-r$ :  $-12 \text{ mmol C m}^{-2} \text{ d}^{-1}$ ) was near the mean of heterotrophic cases within the distribution of 70 LOICZ metabolic estimates obtained from budgets made around the world (compiled by Buddemeier et al. 2002). The denitrification estimate ( $1.9 \text{ mmol N m}^{-2} \text{ d}^{-1}$ ) was also near the mean of estimates from the 70 budgets tabulated by Buddemeier et al. (2002). It was virtually identical with the mean of the literature summary of Seitzinger (1988) for 12 shelf and estuarine studies ( $1.8 \text{ mmol m}^{-2} \text{ d}^{-1}$ ), as well as the modelled estimate of Firth denitrification made by Giles (2001), predicted using organic loading data from Firth benthic biogeochemical field surveys of Nodder et al. (2000). A subsequent study by Nodder et al. (2003) used oxygen consumption incubations and paired C and N isotopic incubations to make direct experimental measurements (still under analysis) of Firth benthic respiration and denitrification, to compare with these budget and model estimates.

These considerations indicate that the estimates of system primary production, respiration and denitrification made here are reasonable in comparison with other studies of temperate coastal regions, including the Hauraki Gulf and Firth of Thames. They will be compared in upcoming research with datasets currently under analysis for the Firth system, derived from field surveys and experiments.

The precision of budgetary estimates can be estimated using a similar ‘bootstrap’ approach as used above, and similar to that implemented by Álvarez-Salgado and Gilcoto (2004), to estimate error on oceanographic variables in budgetary analyses. Net metabolism ( $p-r$ ) can be described as:

$$(\text{residual P flux} + \text{mixing P flux} + \text{river P flux}) \times \text{organic C:P} \quad (3)$$

Residual flux error is dominated by the error of river gauging (estimated to be 8%: A. McKerchar, NIWA, pers. comm.). Error on mean P of Firth and Gulf samples was found to be 4%. These errors were used to generate 100 normally distributed estimates of residual flux and mean P, and their product, residual P flux. Similarly, 100 mixing P flux estimates were created based on the error of the salinity samples (1%) and the residual salt flux (calculated from residual flux and salinity difference), and the error on P samples. The error of river P flux was set at 9%, assuming dominance by the gauging error and small laboratory analytical error. Error on organic C:P estimates was set at 4%, based on Smith et al. (1991). The standard deviation of 100 iterations of (3), above, was taken as the error of its mean estimate distribution and produced a CV of 24%. Thus,  $p-r$  was  $-12 \pm 3 \text{ mmol C m}^{-2} \text{ d}^{-1}$ . Error of denitrification would be expected to be of similar relative magnitude, indicating that denitrification was  $1.9 \pm 0.5 \text{ mmol m}^{-2} \text{ d}^{-1}$ .

The estimates of elemental composition and respiration of mussels are likely to be reasonably accurate, because they are underpinned by relatively straightforward laboratory analyses. The estimates of C and N content for green mussels were virtually identical to those obtained for horse mussels (M. Gibbs, NIWA, pers. comm.). This is taken to suggest that the values of shell C and N assumed for green mussels is similar to horse mussels. In terms of precision, the CV of mDW:tDW was 3.3%. Other errors were assumed similarly small, in comparison with the much larger errors for system production, respiration and denitrification, above.

### 3.4. Comparisons with LAC criteria and biological modelling

In this study we have compared the extraction of carbon and nitrogen by mussel production at various AMA development levels with carbon and nitrogen fixation by Firth primary production. If we assume a linear relationship between Firth-wide and

local farm scales, we could interpret the prediction that the WBMFZ scenario (scenario 3 in Table 4) will extract 0.5% of primary production (over 100% of the Firth), to indicate that 5% of production will be removed over 10% of the Firth. These results would also indicate that primary *biomass* would be reduced by 5% over 10% of the Firth, at WBMFZ fully developed, assuming that the ratio between phytoplankton production and biomass remains constant. This degree of depletion is well below the current LAC criterion that chl-*a* depletion from mussel farming should not exceed 20% over 10% or more of the Firth.

These considerations suggest that at development levels of scenario 5 (three x WBMFZ fully developed), the LAC criterion also will not be exceeded (about 16% depletion over 10% of the Firth). Scenario 5 would, in principle, transpire if the Western Firth AMA were to be fully developed following WBMFZ development. Considering the levels of precision in the estimates, it appears that at maximum development the LAC criterion may be approached.

These system-level estimates of annual-average depletion are similar to those stemming from short-term (three – four week) scenario simulations made by Broekhuizen et al. (2004, in prep.). For a scenario similar to the largest one in this report (3 x WBMFZ), those authors concluded that whilst their simulations indicated that the 20% / 10% threshold would be approached, and perhaps exceeded from time-to-time, it probably would not be exceeded at the annual scale. That conclusion is qualitatively consistent with that reached within this report, although it should be noted that Broekhuizen et al. (2004 in prep.) used farm biomasses that were probably somewhat less (by about 40%) than employed here, for their ‘WBMFZ’ and ‘Wilson Bay fully-developed plus Western Firth’ scenarios.

The fact that these two entirely independent modelling approaches have yielded a similar result with respect to the overall Firth system is encouraging. Both have predicted that is unlikely that phytoplankton depletion in the Firth will approach the current LAC criterion, until AMA development expands to the extent implied by pending applications.

## 4. Acknowledgements

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Zeldis, J. (in press) Water, Salt and Nutrient Budgets for Hauraki Gulf and adjacent Firth of Thames, New Zealand. For LOICZ IPO, Texel, The Netherlands.

## Appendix: Water, Salt and Nutrient Budgets for Hauraki Gulf and adjacent Firth of Thames, New Zealand

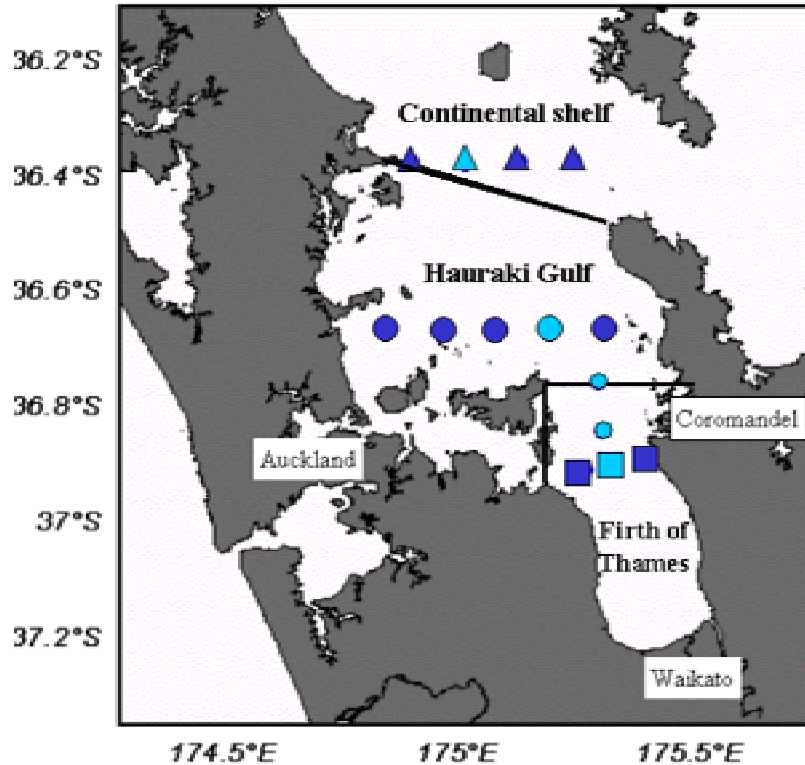
### Introduction

The Hauraki Gulf is a large temperate latitude embayment on the northeastern coast of the North Island of New Zealand (Fig. 1). New Zealand's largest city, Auckland (1.2 million population), borders the Gulf's southwestern shoreline, while the remainder of its catchments are largely pastoral or in native forest. The Gulf supports large aquaculture industries (for mussels and oysters), important natural shellfish and finfisheries, marine reserves, and extensive recreational opportunities among its islands, bays, and open waters. The large population centre, the surrounding intensive pastoral development, and the many natural amenities associated with the Hauraki Gulf, indicate the need for careful resource management in this region.

An important element of resource management in the Gulf is an understanding of factors which force variation in its nutrient dynamics. Accordingly, a water, salt and nutrient budget for the Gulf was developed using LOICZ protocols by Zeldis and Smith (1999), using samples collected in spring and summer 1996-97. The budget allowed estimates of the relative magnitudes of nutrient loading from oceanic and anthropogenic (i.e., Auckland city sewage, and agricultural) sources into the Gulf. The Gulf opens onto a narrow continental shelf subject to upwelling, (Zeldis et al. 2004) and not surprisingly, ocean-derived nutrients were calculated to account for about 60% of the dissolved inorganic nitrogen (DIN) load into the Gulf. River inputs, mainly from pastoral catchments draining into the southeastern Gulf *via* the Firth of Thames (Fig. 1), accounted for about 30%, and Auckland city sewage contributed the remainder. A recalculation of the budget (based on corrected Gulf area and river flow data) indicated a mean water turnover time for the Gulf of about 69 days. The Gulf was found to be moderately heterotrophic, exporting about  $3 \text{ mmol DIC m}^{-2} \text{ d}^{-1}$ , and also to be moderately denitrifying, producing about  $1 \text{ mmol N m}^{-2} \text{ d}^{-1}$ .

The 'Gulf' compartment in the 1999 budget was characterised by samples taken across the centre of the greater Gulf (Fig. 1), and it was assumed that these samples characterised all waters further inshore. However, the budget results suggested that Firth of Thames waters would be reacting to forcing distinct from that of the greater Gulf. The rivers entering the head of the Firth account for the large majority of freshwater input to the Gulf system, so it would be expected that Firth waters would have a higher ratio of riverine to mixing flows, than the greater Gulf. The potentially greater loads of particulate matter and dissolved inorganic and organic nutrients into

the Firth from this input could be expected to elicit C and N fluxes distinct from the greater Gulf, and shelf waters beyond.



**Figure 1:** Place names, sampling stations and system boundaries used in this study. Shelf stations are triangles, Gulf stations are large filled circles and Firth stations are squares. The shelf and Gulf stations are the same as used in the 1999 LOICZ budget (see text). Light blue symbols denote positions used in the contoured sections of Fig. 3.

For these reasons, in 2000-2001 a new set of oceanographic samples was acquired, with the dedicated purpose of estimating a budget that isolated the Firth of Thames as a coastal end-member along the land-ocean gradient. Along with the nutrient metabolism results arising from such a budget, it was expected that important physiographic information, such as estimates of water residence time and nutrient loading rates would be obtained for the Firth of Thames. These results are important because the Firth is now a centre of rapid mussel aquaculture development, with the largest farm in New Zealand recently constructed on its eastern shoreline. The performance of this farm as a production unit is likely to be sensitive to variation in nutrient loading to the Firth, originating from upwelling dynamics offshore and from river input. To estimate the relative importance of oceanic vs riverine nutrient loading to the Firth under these variable conditions, the sensitivity of budget results to differing end-member nutrient concentrations is tested in the present work.

Because the major rivers entering the Firth drain intensively farmed catchments (Waikato district), resource managers have an interest in gauging the impact that runoff of dissolved and particulate nutrients are having on the Firth waterway. An effective way to further this is to understand the relative sizes of the nutrient loading terms to the system (e.g., riverine, oceanic, sewage), and also how such loading is metabolised by the Firth system. All of these aspects make it important to understand physical and nutrient dynamics of the Firth system, as distinct from the greater Gulf.

As well as being more spatially resolved, this new budget differs from the 1999 work in that data were acquired seasonally, with spring, summer, autumn and winter surveys, in 2000-01. Thus, the new data are used to estimate a true 'annual average', rather assuming that spring and summer data represented annual rates, as was done for the 1999 budget. Finally, in the new budget, data were acquired for organic N and P to estimate fluxes of those materials, unlike in the 1999 work which considered only inorganic nutrients.

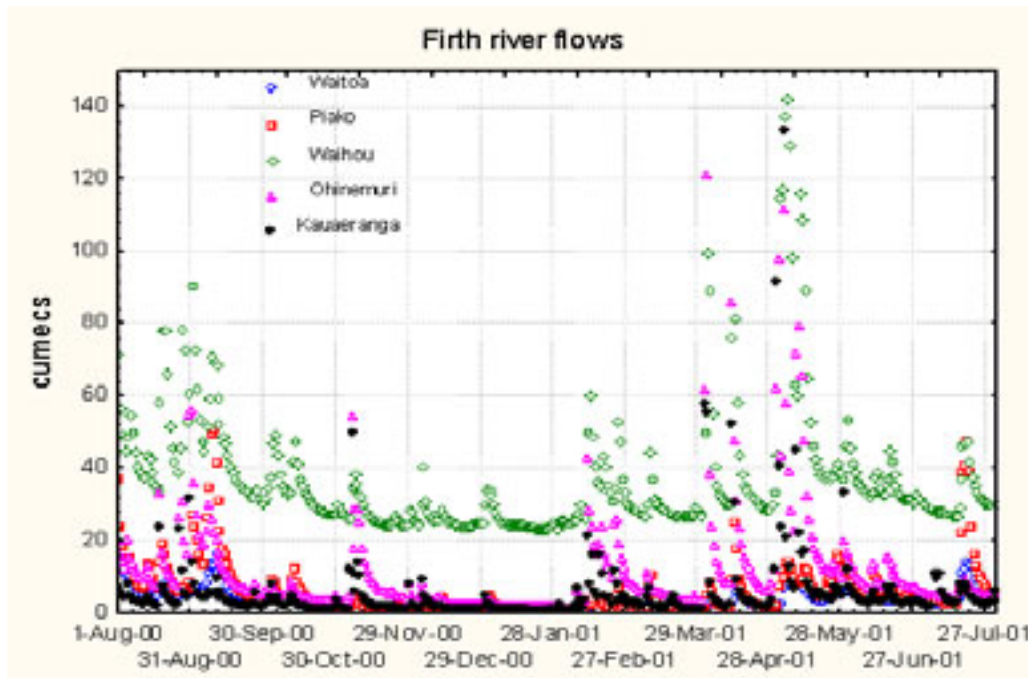
## Methods and Results

The seaward Gulf system boundary (Fig. 1) divided the Gulf system ( $S_{ys2}$ ) waters from the shelf waters ( $S_{ocn}$ ) offshore. Hydrographic survey and mooring data in the area of this boundary indicate frequent cross-isobath flows, showing that the Gulf is very open to the shelf (Zeldis et al. 2004). Further inshore, a boundary isolated the Firth of Thames system ( $S_{ys1}$ ) and Gulf systems ( $S_{ys2}$ ). Salinity gradients are often seen in this area in hydrographic data (J. Zeldis, pers. obs.). The Gulf and Firth systems have surface areas of 2,800 and 1100 km<sup>2</sup>, and volumes of 82 x 10<sup>9</sup> m<sup>3</sup> and 16 x 10<sup>9</sup> m<sup>3</sup>, respectively (U. Shaker, NIWA pers. comm., May 2004), demonstrating the shallower bathymetry of the Firth than the Gulf.

### Freshwater and freshwater nutrients

River flow data from Aug. 1, 2000 to Jul. 31, 2001 were used to characterise the Gulf inflows for the year described by the marine survey data, and were obtained from the NIWA hydrometric database (K. Walter NIWA, pers. comm., June 2004). Flows were prorated by catchment area to scale the gauged rivers to total catchment outflow (using NIWA 'Tideda' software; A. McKerchar, NIWA pers. comm., Nov. 1998). The total inflow to the combined Gulf and Firth systems was about 160 m<sup>3</sup> s<sup>-1</sup>, with 110 m<sup>3</sup> s<sup>-1</sup> into the Firth, and the rest spread around the perimeter of the Gulf. The inflows to the Firth of Thames accounted for most of the total, and were characterised by the 5 rivers shown in Fig. 2. The inflows were greatest in early winter and spring in the budget

period. There is little interannual variation among the means of summed flows for these 5 rivers (mean =  $69 \text{ m}^3 \text{ s}^{-1}$ , s.d. = 10), measured between 1986 and 2004.



**Figure 2:** Daily mean river flow volumes ( $\text{m}^3 \text{ s}^{-1}$ ) for 5 gauged rivers entering the Firth of Thames (NIWA hydrometric database) for the budgeted period.

The 5 Firth rivers drain mainly Waikato scrub and pastoral regions, and forested regions of the Coromandel Peninsula (Fig. 1). The mean nutrient concentrations for the 5 Firth rivers were obtained from Wilson (1998) and B.Vant (Environment Waikato, pers. comm., June 2004). Nutrient concentrations for western Gulf system rivers were estimated from the means of western Gulf rivers documented by Stroud and Wilcox (2000), and those for the eastern Gulf were estimated using the means for the Kauaeranga river from Wilson (1998), because, like the Kauaeranga, they largely drain forested catchments. Pastoral uses dominate the catchments of the first 4 rivers in Table 1, with only the Kauaeranga catchment being largely in forest. The great majority of dissolved inorganic P and N emanating from these rivers is therefore derived from pastoral catchments (Table 1), rather than forested.

There is relatively little variation in monthly mean concentrations of nutrients in these outflows. For example, between 1989 and 1998  $\text{NO}_3^-$  concentrations in the Waihou River at Te Aroha averaged  $88 \text{ mmol m}^{-3}$  with s.d. = 17 ( $n = 120$ ) and DIP averaged  $1.8 \text{ mmol m}^{-3}$  with s.d. = 0.5 (Vant and Wilson 1998). High  $\text{NO}_3^-$  concentrations do not correlate well with high river flow conditions or with extreme rainfall events in this system. Similar patterns obtain for  $\text{NH}_4^+$ .

**Table 1: Annual fluxes (mmol y<sup>-1</sup>) of nutrients delivered from 5 major rivers into the Firth of Thames and estimates for all rivers flowing into the western and eastern Hauraki Gulf for: dissolved inorganic phosphorus (DIP), nitrate (NO<sub>3</sub><sup>-</sup>), ammonium (NH<sub>4</sub><sup>+</sup>), sum of NO<sub>3</sub><sup>-</sup> and NH<sub>4</sub><sup>+</sup>: dissolved inorganic nitrogen (DIN), dissolved organic phosphorus (DOP) and dissolved organic nitrogen (DON). Summed fluxes for each system are also given.**

	DIP	NO <sub>3</sub> <sup>-</sup>	NH <sub>4</sub> <sup>+</sup>	DIN	DOP	DON
<b>Firth of Thames</b>						
Waitoa	1.8E+09	2.4E+10	9.6E+08	2.5E+10	6.6E+08	5.7E+09
Piako	1.2E+09	2.1E+10	1.3E+09	2.2E+10	8.5E+08	9.3E+09
Waihou	2.2E+09	8.9E+10	2.8E+09	9.2E+10	2.2E+09	1.7E+10
Ohinemuri	1.1E+08	1.2E+10	8.8E+08	1.3E+10	2.3E+08	4.2E+09
Kauaeranga	1.7E+07	4.9E+08	1.2E+08	6.2E+08	5.6E+06	8.6E+08
sums	5.23E+09	1.47E+11	6.10E+09	1.53E+11	3.91E+09	3.66E+10
<b>Hauraki Gulf</b>						
Western	8.3E+08	5.1E+10	3.6E+09	5.4E+10	1.9E+09	1.1E+11
Eastern	5.8E+07	2.3E+08	5.8E+07	2.9E+08	2.6E+08	1.5E+09
sums	8.9E+08	5.1E+10	3.6E+09	5.5E+10	2.2E+09	1.1E+11

Groundwater is considered to be a small contributor to inflow, because the landform is composed largely of relatively impermeable sandstones (A. Smaill, Auckland Regional Council, pers. comm. Nov. 1998). Groundwater input was evaluated as 5% of rainfall over the catchments. Rainfall was evaluated using annually averaged data collected between 1986 and 1996, from 4 sites around the Gulf region, and evaporation was estimated over the same period using data from 2 sites (M. Duncan, pers. comm., Nov. 1998; NIWA hydrometric databases).

There are significant discharges of treated sewage effluent, predominately at North Shore, Auckland (Fig. 1), and other smaller discharges further up the west coast of the Gulf. Although the water volume of sewage is small relative to other freshwater input, dissolved P and N are highly concentrated in the effluent (data obtained from M. Shipton, North Shore Regional Council, pers. comm., Nov. 1998), so nutrient flux from this source is significant, relative to other freshwater nutrient sources. Wet and dry atmospheric deposition of P and N were neglected as these are likely to be a small factors in this relatively clean air region.

## Saltwater and marine nutrient sources

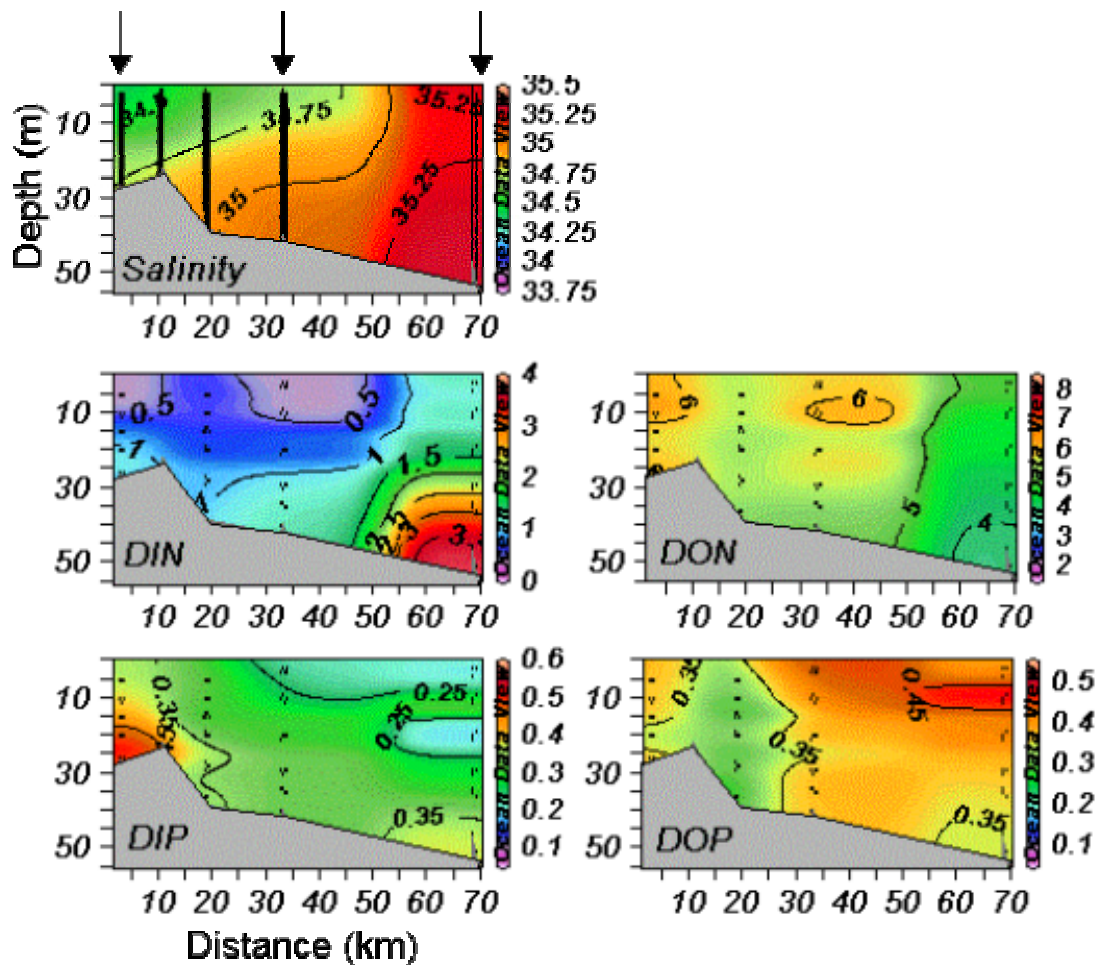
In the annually averaged budget presented here, salinity and nutrient data from all depths on all stations on each transect over all voyages were averaged, to estimate annually-averaged salt and nutrient concentrations in shelf, Gulf and Firth systems. This involved 96, 108 and 50 samples taken in the shelf, Gulf and Firth systems, respectively, divided nearly equally between the 4 surveys. Salinities were determined from SeaBird 911 CTD output (Zeldis et al. 2004) and nutrients were assayed according to methods in Pickmere (1998).

It was considered that annual averaging was unlikely to introduce significant bias in estimated mixing, based on Webster et al. (1999) who conducted sensitivity analyses of various temporal and spatial averaging schemes on idealised LOICZ budgets. High inflow periods into the Firth are of much shorter duration than low flow periods (Fig. 2), and the overall range of salinities in the Firth under high and low flows is not large (~ 2 psu), indicating that ocean end-member mixing clearly dominates river flows in terms of the salt budget. These features suggest that negligible bias in estimated mixing would be incurred by annual averaging (Webster et al. 1999).

Spatial averaging was also applied, in both horizontal and vertical dimensions. The Firth sampling stations were located in the central Firth, clearly ‘down estuary’ of the riverine sources of freshwater and nutrients at its head. As described by Webster et al. (1999), these relative dispositions of sampling sites and freshwater and nutrient sources are unlikely to introduce bias in the estimation of fluxes. Similarly, the Gulf stations are located down estuary of the dominant freshwater source for that compartment (the Firth), and other direct freshwater inputs to the Gulf system are relatively small. The budget was also vertically averaged, rather than stratified into upper and lower water column ‘boxes’. Webster et al. (1999) found that the assumption of vertical homogeneity incurred significant bias in flux estimates only if the estuary was in fact highly stratified. Vertical gradients in Firth of Thames salinity are not large (~0.5 psu: Fig. 3) even in the maximally stratified season (spring: not shown), justifying use of a vertically averaged model.

Seasonally varying upwelling and downwelling over the continental shelf adjacent to the Hauraki Gulf supply lower and higher salinity water, respectively, to the Gulf entrance, but the range of salinities of these waters is not large (*ca.* 0.1-0.2 psu; Zeldis 2004). In contrast, increased river flows cause significantly decreased salinities in Firth and Gulf systems during winter and spring, and decreased flows in summer and autumn allow salinities to rise (*ibid*). Accordingly, over the budgeted period, the horizontal salinity gradient varied seasonally, ranging from 0.3 to 1.1 psu, between the Firth and shelf end-members.





**Figure 3:** Annually-averaged vertical sections of properties with increasing distance offshore, from the Firth of Thames, through the Hauraki Gulf, to the shelf, for salinity (psu), and dissolved inorganic nitrogen (DIN), dissolved inorganic phosphorus (DIP), dissolved organic nitrogen and dissolved organic phosphorus (DOP) ( $\text{mmol m}^{-3}$ ). See Fig. 1 for station positions. The arrows in the salinity plot show the locations of the transects used in the budget. The names and dates of the voyages used to estimate these parameters were: KAH0010 (12-15 Sep.2000; KAH0013 (21-23 Nov. 2000); KAH0105 (12-16 Mar. 2001); TAN0110 (11-13 Jul 2001).

Dissolved nutrients are transported well into the inner Gulf by the residual circulation and also generated locally by mineralisation (Zeldis et al. 2004; Zeldis 2004). Upwelling, while having only a minor depressing effect on Gulf salinities, causes dramatic changes in its near-bed  $\text{NO}_3^-$  concentrations (often 2-3 – fold increases: Zeldis 2004). Thus, there is considerable scope for seasonal variation in oceanic loading of  $\text{NO}_3^-$  between winter/spring and summer/autumn, and also interannually, between years of prevalent upwelling or downwelling (Zeldis et al. 2000). The benthic mineralised  $\text{NO}_3^-$  efflux, on the other hand, appears to be more seasonally constant (Zeldis 2004).

## Water and Salt Budgets

The budget analysis was performed using the LOICZ guidelines (Gordon et al. 1996; David et al. 2000). Residual flows,  $V_{R1,R2}$  for the Firth and Gulf systems were calculated as:

$$V_{R1} = -(V_{Q1} + V_{O1} + V_{G1} + V_{P1} + V_{E1}) \text{ and}$$

$$V_{R2} = -(|V_{R1}| + V_{Q2} + V_{O2} + V_{G2} + V_{P2} + V_{E2}),$$

where subscripts  $R, Q, O, G, P,$  and  $E$  identify volumes of total residual flow, river runoff, sewage, groundwater, precipitation, and evaporation, and subscripts  $1$  and  $2$  refer to Firth and Gulf systems, respectively. Note that in this budget  $V_E$  terms are negative and that the small volumes of sewage water are neglected. Because  $V_{R1}$  and  $V_{R2}$  are negative, residual flow is out of the Firth and Gulf. Note also that implementation of the budget as a multi-box model means that residual flow of the Gulf system (i.e.,  $V_{R2}$  of  $S_{ys2}$ ) is calculated as the sum of the absolute value of  $V_{R1}$  of the Firth system and the freshwater terms affecting  $S_{ys2}$ .

The steady-state balance of salt between the Firth and the Gulf, and between the Gulf and shelf, can be defined by:

$$0 = V_{R1}S_{R1} + V_{X1}(S_1 - S_2) \text{ and}$$

$$0 = V_{R2}S_{R2} + V_{X2}(S_2 - S_{shelf}) \text{ respectively,}$$

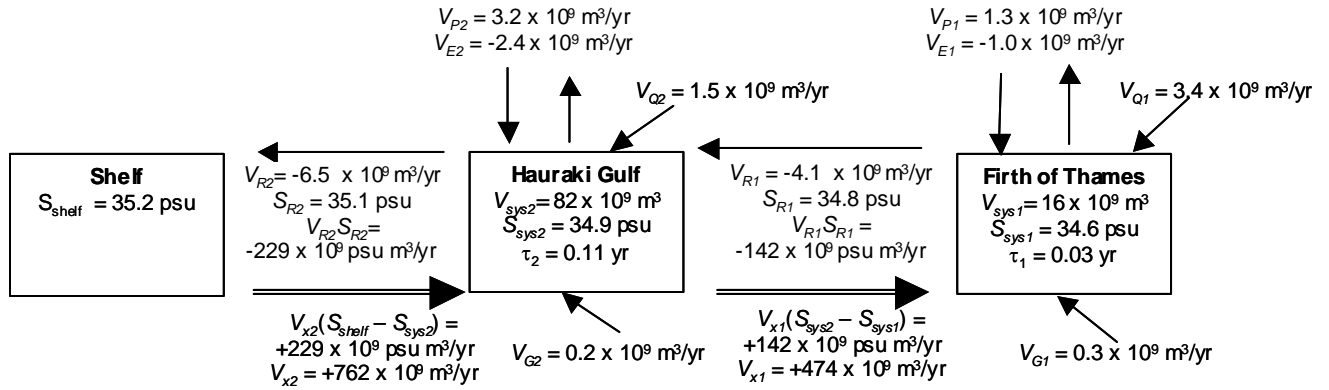
where the salinity of the residual flows ( $S_{R1}$  and  $S_{R2}$ ) are the averages of salinities of  $S_{ys1}$  and  $S_{ys2}$ , and  $S_{ys2}$  and the shelf, respectively. Rearrangement of these expressions allows calculation of  $V_{X1}$  (the mixing between  $S_{ys1}$  and  $S_{ys2}$ ), and  $V_{X2}$  (the mixing between  $S_{ys2}$  and the shelf), required to balance the residual flows of salt.

The mean residence times ( $\tau_{S_{ys1}, S_{ys2}}$ ) of water in the Firth and Gulf systems (with volumes =  $V_{S_{ys1}}$  and  $V_{S_{ys2}}$ ) are calculated as:

$$\tau_{S_{ys1}, S_{ys2}} = \frac{V_{S_{ys1}, S_{ys2}}}{(V_{X1, X2} + |V_{R1, R2}|)}.$$

Residence time for the combined Gulf and Firth systems was calculated using the above equation except that the residual and mixing flows were calculated using a

system salinity formed by the volume-weighted average of the Gulf and Firth system salinities.



**Figure 4:** Water and salt budgets for Firth of Thames and Hauraki Gulf. Variables and subscripts are defined in the text, and arrows indicate directions and relative magnitudes of fluxes between Firth, Gulf and shelf systems.

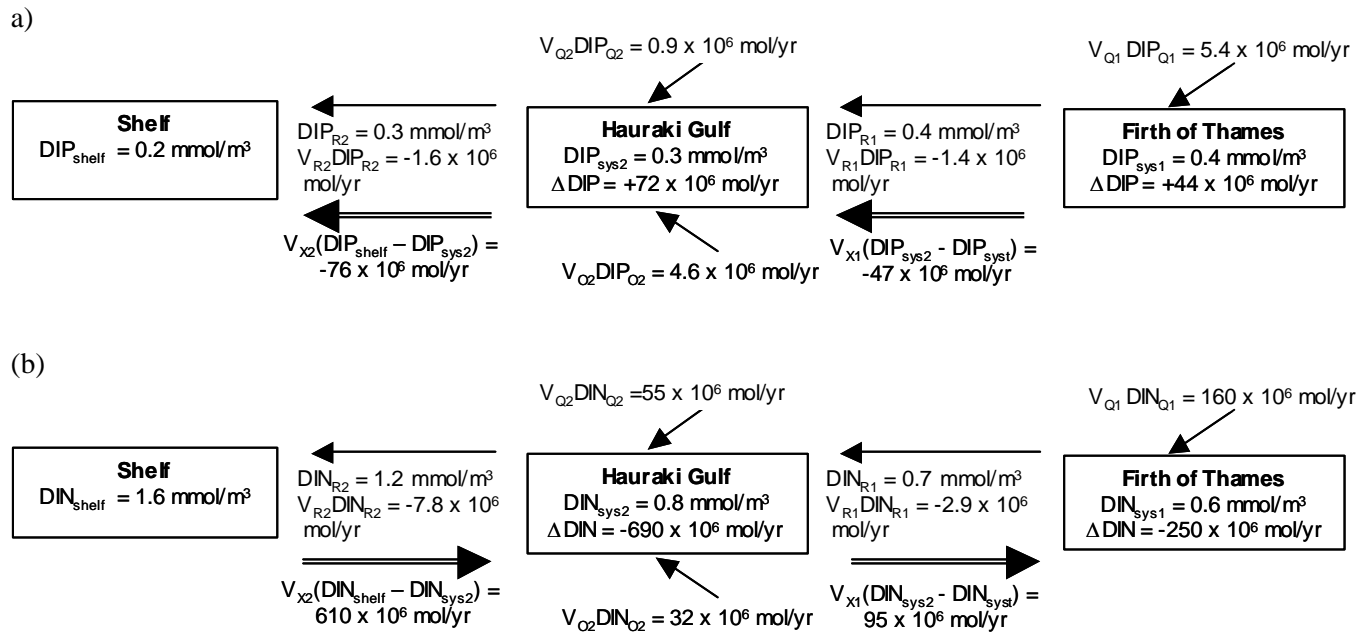
Residence times of 0.03 and 0.11 yr (12 and 39 days) were calculated for the Firth and Gulf systems, respectively (Fig. 4). The calculated residence time for the combined Gulf / Firth systems was 58 days.

### Budgets of non-conservative materials (DIP, DIN, DOP, DON)

Dissolved nutrients which behave non-conservatively in the coastal environment may be assumed to be transported into and out of the system by the same residual flows and mixing processes as water and salt, derived above. These terms are represented by the inputs and outputs shown below. However, the flux of these reactive materials includes an additional term,  $\Delta Y$ , to account for the net non-conservative behaviour (release - uptake) within the system:

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

For the non-conservative flux of DIP,  $\Delta DIP$  (Fig. 5 a), this expression was evaluated as the sum of riverine, sewage, residual and mixing flows.



**Figure 5:** (a) DIP and (b) DIN budgets for the Firth of Thames and Hauraki Gulf. Variables and subscripts are defined in the text, and arrows indicate directions and relative magnitudes of fluxes between Firth, Gulf and shelf systems.

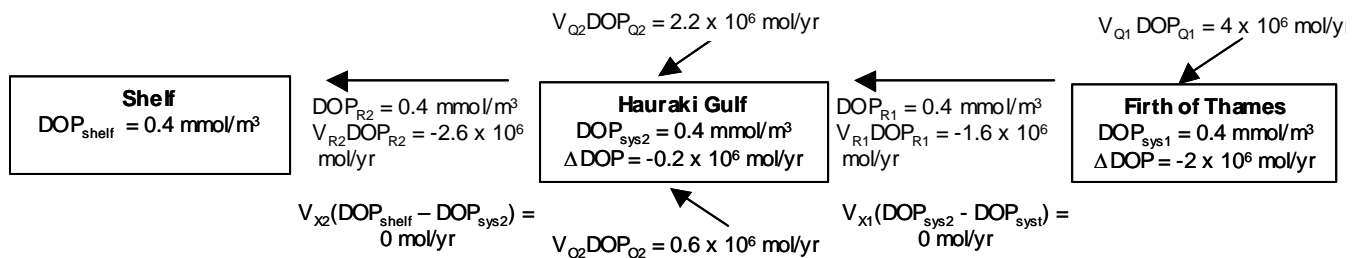
The positive values of  $\Delta DIP$  for Firth and Gulf systems indicates that these systems have an internal DIP source. That is, internal system reactions are generating DIP over particulate organic P, suggesting that they are net respiring, oxidative systems. Therefore, the differences between production and respiration ( $p-r$ ) for the systems are apparently negative. The production of DIP on an areal basis is about 40 and 26 mmole DIP  $m^{-2} y^{-1}$  in the Firth and Gulf systems, respectively. If the Redfield relationship of C:P of 106:1 is assumed for these plankton-based systems, they are producing about 4200 and 2800 mmol C  $m^{-2} y^{-1}$ , respectively. It appears that the Firth is somewhat more heterotrophic than the Gulf. These values for the two systems place them toward the heterotrophic end of the distribution of 70 LOICZ metabolic estimates obtained from budgets made around the world (compiled by Buddemeier et al. 2002).

For the non-conservative flux of DIN,  $\Delta DIN$ , similar calculations apply as for  $\Delta DIP$  (Figure 5 b). The negative values of  $\Delta DIN$  indicated that the Firth and Gulf systems are net sinks for DIN. These observed values of  $\Delta DIN$  were equivalent to -230 and -250 mmol  $m^{-2} yr^{-1}$ . If DIN were released in a Redfield ratio (16:1) with respect to DIP, the expected DIN fluxes ( $\Delta DIN_{exp}$ ) in these systems would be +560 and +420 mmol  $m^{-2} yr^{-1}$ . The discrepancies (-870 and -670 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 the Firth being more active than the Gulf. These

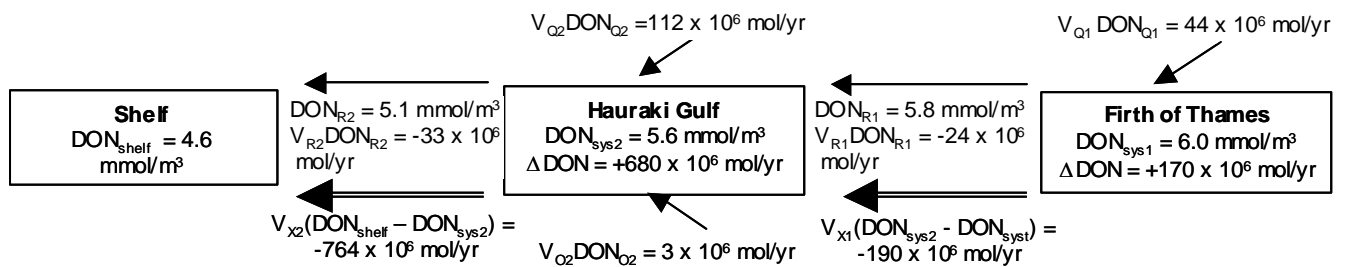
estimates are near the mean of (*nfix-denit*) tabulated by Buddemeier et al. (2002). Non-conservative fluxes of organic P (DOP) and N (DON) were also budgeted. For DOP, (Fig. 6 a), the small values of  $\Delta DOP$  for Firth and Gulf systems indicated that these systems are essentially neutral in terms of transformations of organic P.

The positive values of  $\Delta DON$  (Fig. 6 b) indicated that the Firth and Gulf systems appeared to be generating DON. These observed values of  $\Delta DON$  were equivalent to 155 and 246  $\text{mmol m}^{-2} \text{yr}^{-1}$ . If DON were generated in a Redfield Ratio (16:1) with respect to DOP, the expected DON fluxes ( $\Delta DON_{exp}$ ) in these systems would be -34 and -1  $\text{mmol m}^{-2} \text{yr}^{-1}$ . The discrepancies (190 and 247  $\text{mmol m}^{-2} \text{yr}^{-1}$ ) indicate that the systems are generating DON on a net basis, albeit at considerably slower rates than they are denitrifying inorganic N (see above).

(a)



(b)



**Figure 6:** (a) DOP and (b) DON budgets for the Firth of Thames and Hauraki Gulf. Variables and subscripts are defined in the text, and arrows indicate directions and relative magnitudes of fluxes between Firth, Gulf and shelf systems.

## Discussion

The annual average water residence time for the Firth was estimated to be about 12 d, while the estimated residence time for the combined Gulf / Firth system was about 58 d. The latter estimate was somewhat less than in the 1999 budget (69 d, recalculated),

which may have been partly due to having accounted for river flows draining into the western and eastern Gulf (in addition to the Firth), which was not done in the 1999 work. It should also be noted that the 1999 budget was made using samples collected only from late spring to late summer, whereas in the present study a true annual cycle was sampled, which could have included a greater dynamic range of mixing conditions.

As in the 1999 budget, the Firth and Gulf systems were found to be net exporters of DIP and importers of DIN, supporting the original findings that these coastal systems are net heterotrophic and denitrifying. It was also clear that the mineralisation and denitrification fluxes were larger than the sums of riverine and oceanic mixing fluxes of dissolved inorganic and organic nutrients. This means that the oxidation and denitrification must be fuelled by import of particulate organic matter, similar to that shown by Smith et al. (1991) for Tomales Bay. Preliminary calculations (not shown) suggest that tidal mixing rates of POC and PON across the Gulf-Firth system boundary are sufficient to easily meet this demand for particulate carbon and nitrogen, even without accounting for riverine particulate inputs (which are not presently known).

The values of Gulf and Firth system heterotrophy in the present study ( $\sim 3$  and  $4 \text{ mol C m}^{-2} \text{ y}^{-1}$ ) were considerably higher than the 1999 Gulf system estimate of  $\sim 1$ , the reasons for which are not clear. A possible reason may be that the present budget was truly annual, whereas the 1999 budget was restricted to spring and summer periods. As noted above, a greater mean rate of mixing ( $V_{x2}$ ) between shelf and Gulf was estimated in the present budget than in 1999 ( $2.3$  vs  $1.6 \times 10^{11} \text{ m}^3 \text{ psu y}^{-1}$ ), possibly reflecting improved specifications of river flow in the budget. However, essentially the same DIP contrast as in the 1999 budget was found between the shelf and Gulf systems. This was maintained in the face of greater mixing, indicating a stronger P source in the present budget.

Primary production ( $^{14}\text{C}$ ) estimates collected seasonally at the entrance to the Firth of Thames (Gall et al. 2002) indicate mean annual fixation of about  $\sim 58 \text{ mmol C m}^{-2} \text{ d}^{-1}$ . The values of primary production minus respiration ( $p-r$ ) estimated here ( $\sim -12$  and  $-8 \text{ mmole C m}^{-2} \text{ d}^{-1}$  for the Firth and Gulf, respectively), suggest absolute values of heterotrophy of  $\sim 70$  and  $66 \text{ mmol C m}^{-2} \text{ d}^{-1}$  in the Firth and Gulf, and ratios of production to respiration of  $\sim 0.84$  and  $0.88$ .

Another feature of DIP metabolism was the stronger source detected for the Firth than for the greater Gulf. Both systems appear to import organic matter, but the Gulf appears to balance the decay of this matter with production more than does the Firth. This may be explained by likely higher areal loads of particulate organic matter into

the Firth, which receives the great majority of river inputs into the systems, mainly from pastoral catchments. Deposits of fine material in inner Firth benthos (shown on sediment charts of the Firth: Carter and Eade 1980), support this proposition. Thus, the Firth was highly heterotrophic, and the adjacent Gulf waters were less so. The adjacent continental shelf, on the other hand, imports significant amounts of nutrient on-shelf and exports significant amounts of fixed carbon off-shelf during spring and early summer (Zeldis 2004), and therefore operates net-autotrophically at those times, while in late summer it appears more balanced between auto- and heterotrophy. Thus, the present findings are consistent with Smith and MacKenzie (1987) who argued that the terrigenous organic load reaching the ocean should be largely trapped and oxidised within the land-sea interface, eliciting a primary production to respiration ratio there less than 1.0, and that further offshore, the ratio should rise back toward a value marginally in excess of 1.0.

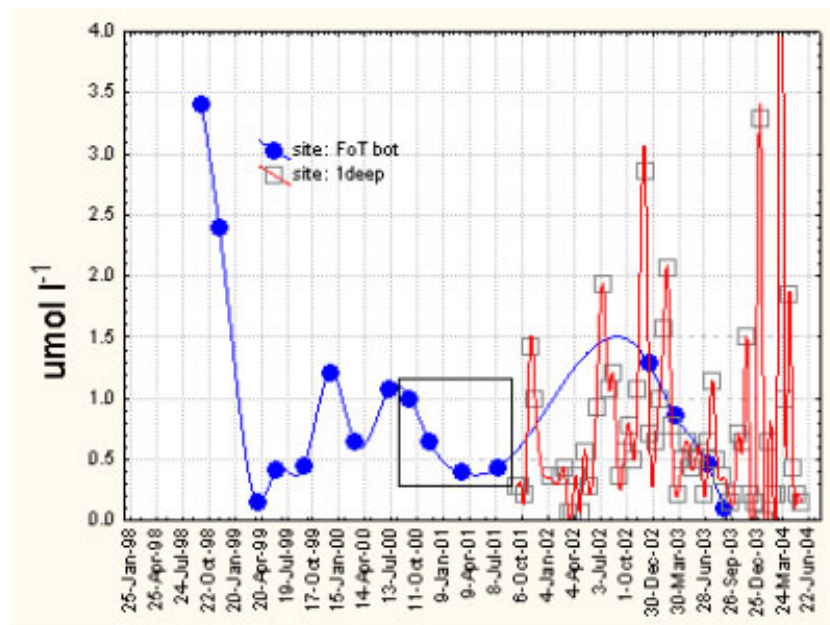
The net denitrification values found in the present study were about twice that in 1999. Strongest denitrification was in the Firth system, probably again reflecting organic particle loading from its rivers. Biogeochemical studies using paired C and N isotopes recently made in the Firth benthos will provide direct measurements of denitrification to compare with the budget estimates made here. Metabolism of DIN and DON had opposite sign in this study (in common with Smith et al. (1991) for Tomales Bay), presumably indicating conversion of particulate N to DON during mineralisation.

Interesting comparisons are possible between the N and P fluxes from river, sewage and ocean sources, using these budget calculations. For the Firth, the flux of DIN from rivers (i.e.,  $V_{Q1}DIN_{Q1}$ ) contributed about 65% of the total of river + ocean supply (i.e.,  $V_{Q1}DIN_{Q1} + V_{X1}(DIN_2 - DIN_1)$ ), with mixing between the Firth and the greater Gulf contributing 35%. For the Gulf, rivers supplied only 8% of DIN, and sewage (Auckland City) contributed 5%, demonstrating the dominance of ocean supply.

For the period of this budget (Aug. 2000-Jul. 2001) it was clear that most DIN was supplied to the Firth by its rivers. However, during most of the budgeted period, the Gulf and Firth region was in an oligotrophic state, with relatively low near-bed  $\text{NO}_3^-$  concentrations detected in time-series of nutrient sampling in the outer Firth (Fig. 7). These data, collected since 1998, have shown protracted phases of higher or lower  $\text{NO}_3^-$  concentrations in this area, each lasting a number of months.

These phases appear to be driven by low-frequency variation in periods of upwelling- and downwelling-favourable winds on the adjacent continental shelf, and cross-shelf advection of resulting high and low nutrient waters into the Gulf (Zeldis et al. 2004, Zeldis 2004). Changes in upwelling behaviour can cause near-bed Gulf  $\text{NO}_3^-$  concentrations to vary 2-3 fold, although as described previously, the salinities of the

upwelled and downwelled waters are very similar. For example, between the 2000-01 period of this budget and mid- to late 2002, there was a transition from downwelling- to upwelling- favourable wind stress on the shelf and  $\text{NO}_3^-$  concentration doubled in the outer Firth (J. Zeldis unpubl. data 2003; Fig. 7). However, there was almost no change in mean Firth salinities or river flow rates (means of 64 and 75  $\text{m}^3 \text{s}^{-1}$  for the two Aug.-Jul periods), nor did DIP and DIN concentrations change within the river water (Environment Waikato: data provided June 2004). The plasticity of ocean loading, and the relative stability of riverine loading, suggests that it is the former which has the most potential to drive interannual variation in Firth DIN loads.



**Figure 7:** Time-series of  $\text{NO}_3^-$  sampling at monitoring stations in the outer Firth conducted quarterly since Sep. 1998 in the NIWA Cross-Shelf Exchange (C-SEX) programme (blue) and conducted fortnightly at the deep control site of Wilson Bay (Group A) mussel farm monitoring programme (red; Group A consortium pers. comm. June 2004). The  $\text{NO}_3^-$  concentrations at the times of the 4 seasonal surveys used in the LOICZ budget (See Fig. 3) are enclosed in the rectangle. Note protracted phases of higher  $\text{NO}_3^-$  in mid- to late 1998, in late 1999 to mid-2000, mid- to late 2002, and late 2003 to early 2004. Data were fitted by spline fits.

This hypothesis was investigated by testing the response of the budget to increased system DIN concentrations, i.e.,  $\text{DIN}_{\text{sys}1,2}$ . When  $\text{DIN}_{\text{sys}1,2}$  were doubled and trebled to emulate increased upwelled supply, but river inputs held constant, the percentages of river supply of DIN of the total DIN supply into the Firth decreased from 65% to 45% and 36%. This demonstrated that during upwelling phases the ocean supply contributes most DIN to the Firth. Perhaps more importantly, however, it confirmed that it is upwelling dynamics which have the greatest potential to cause long-term variation in Firth DIN loading. Although during oligotrophic periods river supply



contributes most DIN, given that river flood events are ephemeral (lasting only a few days; Fig. 2), and that annually-averaged river flows and nutrient concentrations vary relatively little compared to the protracted (i.e., multi-month) changes in nutrient loading from upwelling, it is apparent that the major source of long-term variation in DIN supply to the Firth of Thames originates from mixing with the adjacent Hauraki Gulf, and shelf waters beyond.

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