Firth of Thames Water Quality and Ecosystem Health

A Synthesis

Prepared for Waikato Regional Council
and DairyNZ under separate contracts

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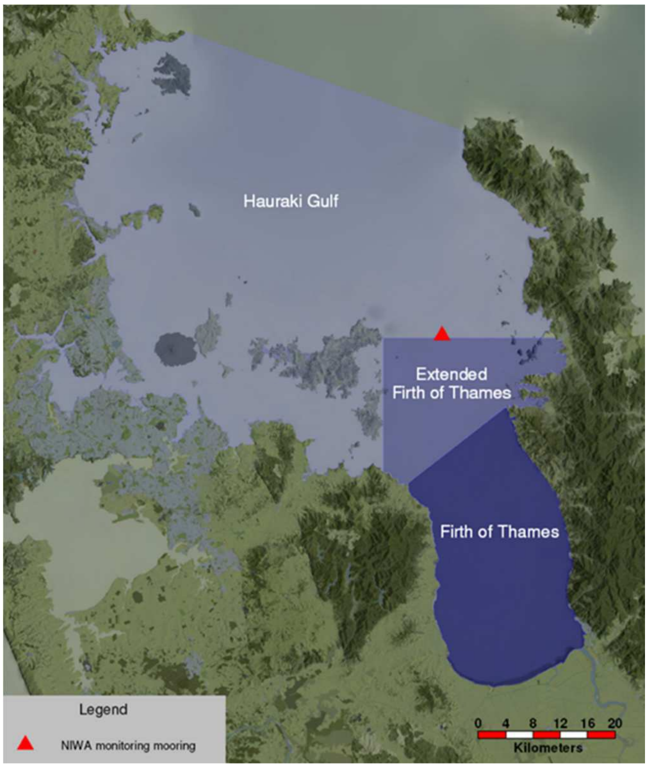
Contents

Key points

Geographic zones

- Place names used in this report: the Firth of Thames, the extended Firth of Thames, and the Hauraki Gulf. The red triangle shows the location of the extended-Firth monitoring site.



Physical setting

- The Firth of Thames is an estuarine embayment occupying the Hauraki Depression bounded to the east and west by the Coromandel and Hunua Ranges, respectively.
- Prior to human habitation the Hauraki Plains was mainly native forest-clad. It is largely cleared of native forest today and dominated by agricultural landuse.
- The Firth receives runoff primarily from the Waihou River and the Piako River, which drain the Hauraki Plains.
- Tidal and wind-driven currents, mixing, and stratification are important hydrodynamic processes that influence all biogeochemical processes in the Firth of Thames and the wider Hauraki Gulf.

Sediments

- Fine sediments have already impaired and continue to affect ecosystem health in the Firth of Thames.
- Land clearance prior to the conversion of the Hauraki Plains for agriculture contributed much of the fine sediment in the Firth of Thames today.
- Present-day inputs of sediment from the Waihou and Piako Rivers account for only 40% of the estimated 430,000 t y^{-1} of sediment currently depositing in the southern Firth of Thames. The apparent discrepancy is likely to be due to the reworking by waves and currents of

legacy sediments deposited in the Firth during large-scale deforestation and mining activities that occurred during the late 1800s to early 1900s.
- Sediments are now accumulating at rates 2–10 times greater than 90 years earlier.
- Monitoring of intertidal regions of the southern Firth of Thames indicates little ongoing change to benthic fauna from changes to seabed mud content over the last decade.

Nutrients

- There are both oceanic and land sources of nitrogen to the Firth of Thames.
- At least when there is no strong ocean upwelling (which is the case for about 90% of the time), inputs from the land are the dominant source to the total nutrient loading of the Firth of Thames.
- Nitrogen loads in rivers draining to the Firth have been stable or increasing only slowly for at least 20 years, whilst phosphorus loads have reduced.
- Dissolved inorganic nitrogen and dissolved organic nitrogen at the extended-Firth monitoring site have increased over the past 15 years. Dissolved inorganic phosphorus has not changed but dissolved organic phosphorus has reduced over the past 15 years.
- The upward trend in nutrient runoff from the Waihou River is not large enough to fully explain the upward trend in nitrogen at the extended-Firth monitoring site. This points to a complex set of causes, possibly including changes to oceanic inputs, terrestrial inputs, physical oceanography and/or denitrification efficiency.
- Further work is needed to determine the nature and causes of the observed change in nitrogen levels within the extended Firth, including whether this is more widespread and continuing.

Phytoplankton and bacteria

- There are more phytoplankton in the Firth than in the extended Firth. Both of these areas contain more phytoplankton than the wider Hauraki Gulf. Primary production rates follow a similar pattern.
- Nitrogen from the land is one factor responsible for the higher phytoplankton levels in the Firth. Other factors are oceanic sources of nitrogen and physical processes such as mixing and water-column stratification that enhance phytoplankton production through effects on nutrient and light availability.
- Phytoplankton abundance and, to a lesser extent, biomass at the extended-Firth monitoring site have increased over the past 15 years. These changes are consistent with the trend in nitrogen at the extended-Firth monitoring site over the same period.
- Phytoplankton composition has also changed, resulting in more small phytoplankton and more large diatoms.
- The decay of phytoplankton and bacterial respiration are linked to seasonal oxygen depletion and pH depression.

Dissolved Oxygen

- The available data show that the Firth of Thames is generally well oxygenated.
- There are seasonal (autumnal) low-oxygen (60–70% saturation) events in the bottom waters at the extended-Firth monitoring site. These events occasionally penetrate into the upper water column and shoreward into the Firth.
- At least two different processes are likely to be contributing to the low-oxygen events in the bottom waters at the extended Firth of Thames: upwelling of high-salinity, low-oxygen cold

water from offshore, and the mineralisation of organic matter in the water column, which consumes oxygen. We believe that latter to be the dominant driver of the autumnal DO decline.

pH

- pH has only been measured in the extended Firth of Thames since 2009, which limits our understanding of long-term change.
- Seasonal patterns indicate a pH minimum of 7.9 during autumn low-oxygen events, rising to pH 8.1 in spring.

Assessments of water quality and ecosystem health

The available information allows us to draw the following conclusions:

- Fine sediments in the Firth of Thames are largely the legacy of past human activities. As a result there are limited opportunities to mitigate sediment effects.
- The almost-complete collapse by the late 1960s of hard, biogenic reefs in the Firth composed of bivalves, sponges, ascidians, bryozoans and cnidarians, has been well documented. The modern sediment macrobenthic community of the Firth of Thames is adapted to the muddier post-reef-collapse conditions and is likely to be quite resilient to ongoing deposition of fine sediment.
- Even if catchment sediment inputs were to be turned off instantly, the prospects for a natural recovery of the Firth benthic ecosystem to a pre-reef-collapse state would be slim.
- The Firth and the extended Firth are sensitive to nutrient enrichment, meaning that symptoms of eutrophication are not likely to be suppressed by physical factors (such as turbid water/low light, short water residence time, and strong vertical mixing of the water column).
- The Firth and the extended Firth are now mesotrophic.
- The Firth of Thames will at least have been “less mesotrophic” prior to catchment deforestation and subsequent development in the catchment. Some simple figuring suggests the Firth may have been oligotrophic.
- Ocean-side loading prior to the historical land clearance and development of the Hauraki Plains was likely to have contributed a much larger percentage to a much lower overall nutrient load to the Firth.
- Denitrification is likely to be an important ecosystem service in the Firth that reduces the risk of eutrophication.
- A reduction in land-side nutrient inputs will reduce the organic-matter load of the Firth and the consequent oxygen depletion that occurs in the extended Firth towards the end of the phytoplankton growth season (late summer to early autumn).
- However, we cannot yet make any quantitative predictions of what changes might ensue following any specific reduction in land-side nutrients.
- Without a return to the former sediment macrobenthic community a full recovery to the pre-catchment-development pattern of nutrient cycling and water quality in the Firth seems unlikely.

The data are not available to make a full assessment of water quality and ecosystem health. This report identifies gaps and priorities for future work that will enable more comprehensive assessments to be made in the future.

Executive summary

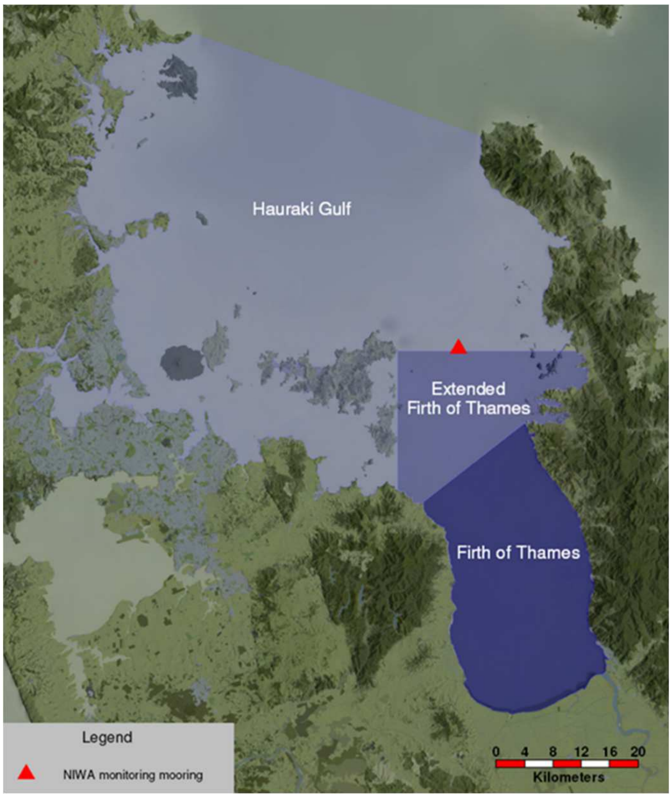
Waikato Regional Council and DairyNZ share questions around water quality in the Firth of Thames. The questions relate to sediments, nutrients, phytoplankton/bacteria, dissolved oxygen and pH (acidification).

The objective of this report is to assess, where possible, the water quality and ecological health of the Firth of Thames, identify information gaps and recommend priorities for future work.

This report is complemented by a data report (Zeldis et al., 2015, NIWA Client Report No. CHC2014-123, prepared for Waikato Regional Council and DairyNZ), which describes the data that NIWA has collected in the Firth of Thames and Hauraki Gulf over the last 20 years.

Geographic zones

- Place names used in this report: the Firth of Thames, the extended Firth of Thames, and the Hauraki Gulf. The red triangle shows the location of the extended-Firth monitoring site.



Sediments

- Intertidal flats in the southern Firth have been accreting for the last 90 years at rates that are an order of magnitude greater than rates that have been observed in intertidal regions of other North Island estuaries.
- Accumulation of mud has permitted widespread mangrove expansion.
- Intertidal flats appear to be accreting “legacy” sediments that are being transported shoreward from the subtidal zone by waves and currents.
- Needham et al.’s (2014) review of the inner Firth’s intertidal benthic macrofauna and surface sediment concluded there was no evidence of ecologically significant changes to either sediment characteristics or indicator taxa over the past 10 years of monitoring.

- The inner, subtidal Firth is depauperate in macrofauna and infauna relative to the central Firth. The most likely reason for this is that the inner Firth is muddier.

Nutrients

- 15 years of measurements at the extended-Firth monitoring site show that dissolved inorganic nitrogen (DIN; the sum of nitrate and ammonium) is abundant in the upper water column only during winter and spring. The most likely reason is that uptake of DIN by primary production is limited by low light at those times. In summer and autumn, when there is plenty of light, DIN in the upper water column is drawn down, which is most likely because of uptake by primary production.
- Over the 15-year measurement period, DIN integrated over the water column increased at a rate of about 5% y^{-1}.
- We looked at possible reasons for the trend in DIN. One candidate was that the upwelling regime has changed (upwelling, driven by westerly winds, brings cool, nutrient-laden oceanic water onto the shelf), however a preliminary analysis yielded no evidence for that. Another possibility was that there has been a change in the nutrient runoff from the land. There does not appear to have been a sufficient upward trend in nutrient runoff from the Waihou River to fully explain the upward trend in nitrogen at the extended-Firth monitoring site.
- A possible contributor to the trend in nitrogen at the extended-Firth monitoring site is that there has been a change in denitrification efficiency, caused by increased organic matter loading to the seabed, and resulting in a decreased capacity of the system to vent nitrogen to the atmosphere.
- We view our analysis of the water-column-integrated data as only a first step towards identifying and understanding trends. The nutrient data exhibit vertical structure over the water column, which is lost by depth-integrating the data.

Phytoplankton and bacteria

- Phytoplankton biomass is generally greatest in spring and least in winter. Biomass is widely distributed in spring, but becomes progressively restricted to inshore areas (especially the Firth) from summer through winter. In the outer Firth, biomass is greatest in the upper water column in spring, but increases noticeably at depth in autumn. Primary production rates follow a similar pattern.
- Chlorophyll *a* and phaeopigment in the lower water column (greater than 20 m below the water surface) at the extended-Firth monitoring site increased over a 15-year monitoring period. There was no trend for chlorophyll *a* or phaeopigment in the upper water column (down to 20 m below the water surface).
- Cell counts (integrated over the water column) of total microphytoplankton showed a significant increasing trend of 6.9% y^{-1} over the 15-year monitoring period.
- Biomass (integrated over the water column) of total microphytoplankton also showed an increasing trend, about 2.5% y^{-1}, over the 15-year monitoring period, although this trend, with an associated p value of 0.07, was not statistically significant at the 95% confidence level.
- A community change has occurred over the 15-year period which includes more numerous smaller phytoplankton and also more numerous large diatoms.
- The overall changes (increasing abundance and, to a lesser extent, biomass of total microphytoplankton) are consistent with what might be anticipated if nutrients have become more abundant.

Dissolved oxygen

- Whilst we have long time series of dissolved oxygen (DO) at one site (in the extended Firth), we have fewer data from other sites. Thus, we cannot make conclusive statements about the oxygen status of the entire region. Nonetheless, the data do reveal temporal and spatial patterns, in particular, of occurrences of low dissolved oxygen at the extended-Firth monitoring-site.

- At the extended-Firth monitoring site, where we have 15 years of data, the upper 20 m of the water column was generally well oxygenated, with greater than 90% DO saturation for much of the year. In summer and autumn, when the water column was stratified, DO typically reduced to about 60–70% saturation at levels in the water column greater than 20 m below the surface. Occasionally, 40% DO saturation has been measured.
- These low-DO events occasionally penetrate into the upper water column and shoreward into the Firth.
- The autumnal subsurface DO depletion is more intense at the extended-Firth monitoring site than it is in the Firth. A likely explanation is that the shallower water in the Firth is better mixed.
- We attribute the seasonal depletion of DO at the extended-Firth monitoring site to a combination of at least two factors: strong stratification of the water column in late summer and autumn that inhibits oxygen exchange with the atmosphere, which otherwise would replenish the DO in the lower water column; and consumption of oxygen by microbial respiration of sinking organic matter that has accrued from primary production in the immediately preceding spring and early summer.
- The cold, high-salinity water that sometimes upwells from deep in the ocean onto the coastal shelf also tends to have low oxygen concentrations. Nonetheless, we do not believe that this is the driver of the annual oxygen depletion that occurs in late summer/early autumn.
- We have conducted a trend analysis of the DO data divided into two depth bins: an upper bin (the top 20 m of the water column) and a lower bin (everything below that). Both exhibited no statistically significant trend over time.

pH

- pH in the water column varies seasonally and is at its lowest in autumn. The pH minimum coincides with autumnal maxima in oxygen depletion and respiration. From this, we can infer that the same combination of physical and metabolic processes that we believe to be driving DO is also driving the carbonate system.
- We have been observing carbonate system dynamics since 2009 but complete records started only with the 2010 survey. This is too short a record to say anything about trends in the carbonate system.

Mineralisation of organic matter

- At all sites that we have made measurements (which includes the Firth, the extended Firth and the inner Hauraki Gulf), there was net oxygen consumption by the sediments. This means that the bed sediments are net heterotrophic, that is, respiration exceeds production. This was found to be the case regardless of water depth or bed-sediment type. Bed sediments in the Firth were about twice as heterotrophic as bed sediments in the extended Firth.
- Measurements of pelagic oxygen demand in autumn also showed strong net heterotrophy, with the rate of oxygen drawdown by respiration at inner-Firth sites being about twice the rate at extended-Firth sites.
- Comparing our data (measured fluxes of O_2 and, by implication, CO_2) with data reported from numerous Australian estuaries, we infer that denitrification efficiency (proportion of the nitrogen entering the seabed that is subsequently denitrified) may be maximum in the extended Firth and close to maximum in the inner Firth. Denitrification efficiency is dependent on the rate of input of organic matter to the bed sediments and can be suppressed by excessive loading. Denitrification measurements are required to assess if further increases in organic matter loadings to the seabed would have an effect on denitrification efficiency.

Budgets

- We developed a water budget, a salt budget and a carbon/nutrient budget for the Hauraki Gulf, extended Firth, and Firth of Thames. These help us to understand the relative importance of sources and the exchanges between different parts of the system.
- Because of data limitations, the budgets for the Gulf are valid for spring, summer and winter, while those for the Firth are valid for spring, summer and autumn. The budgets represent the conditions that prevailed during 2000–2001 surveys; at this time river flows were either close to average (for spring and autumn) or about 60% of average (for summer and winter). Sampling did not include conditions of strong upwelling.
- The budgets show that:
  - Rivers that drain to the Firth contribute 57% of total N inputs (DIN + DON + PON) and 87% of DIN inputs to the Firth, with the remainder coming from offshore.
  - For the Firth, the excess of respiration over production (i.e., the net heterotrophy) must be subsidised by net import of substantial amounts of labile organic carbon from the land and/or from offshore.
  - The Firth appears to be a large denitrifier. About 73% of the total nitrogen export from the Firth appears to be as N_2 gas that results from denitrification. This may help to buffer the system against nitrogen loading from terrestrial and marine sources.
  - On average, nitrogen in the Firth cycles about three times through the production–decomposition cycle before being lost to denitrification or (to a lesser extent) hydrographic export. This “amplifies” the effects of nitrogen imported to the Firth.

Assessments of water quality and ecosystem health

Sediments

- The almost-complete collapse by the late 1960s of hard, biogenic reefs composed of bivalves, sponges, ascidians, bryozoans and cnidarians, which has been attributed to dredge fishing during about 1910 to 1968 that removed extensive reefs of green-lipped mussels, has been well documented. Despite dredging never recommencing, the reefs have not recovered.
- The modern sediment macrobenthic community of the Firth is adapted to the muddier post-reef-collapse conditions and is likely to be quite resilient to ongoing deposition of fine sediment. Even if catchment sediment inputs were to be turned off instantly, the prospects for a natural recovery of the Firth ecosystem to a pre-reef-collapse state would be slim.

The current trophic state of the system

- The Firth and the extended Firth are sensitive to nutrient enrichment (meaning that symptoms of eutrophication are not likely to be suppressed by physical factors such as turbid water/low light, short water residence time, and strong vertical mixing of the water column). This makes the Firth more susceptible to adverse effects from sediment and/or nutrient inputs from the land than either shallower, more rapidly flushed estuaries or coastal waters along an energetic, open coastline.
- Our data show that the Firth of Thames seasonally exceeds the NOAA ASSETS 5 mg m^{-3} chlorophyll *a* threshold for “medium impacts”. This threshold is rarely exceeded at the extended-Firth monitoring site but it is frequently approached. Both regions are below the 20 mg m^{-3} “high impact” threshold. Thus, the ASSETS classification places the Firth in the “medium impacts” category while the extended Firth is at the upper end of “low impacts”.
- Based primarily on our primary-production data, we would describe the current state of the Firth and the extended Firth as mesotrophic, where mesotrophic is the intermediate state between oligotrophic and eutrophic.

The pre-development trophic state of the system

- In our opinion, the Firth of Thames will at least have been “less mesotrophic” and may have been oligotrophic prior to catchment deforestation and subsequent development in the catchment. We have no direct data to support our estimation of any previous trophic state of the Firth (that is, we do not have any actual measurements from the pre-historic period).

The contribution of land runoff to nutrients

- It is likely that the balance between land-side and ocean-side nutrient loading was different prior to the historical land clearance and landuse intensification of the Hauraki Plains, specifically that ocean-side loading was likely to have contributed a much larger percentage to a much lower overall nutrient load to the Firth.

Cause(s) of the nitrogen trend at the extended-Firth monitoring site

- The cause of the trend in nitrogen at the extended-Firth monitoring site is likely to be complex, possibly including changes to oceanic inputs, terrestrial inputs, physical oceanography and/or denitrification efficiency.

Effects of low dissolved oxygen

- Oxygen minima below 6 mg L^{-1} in the lower water column at the extended-Firth monitoring site (with penetration into the upper water column on occasion), when combined with the uncertain response of kingfish/hapuka to oxygen status, warrant further investigation vis-à-vis management of the Coromandel Fish Farm Zone, which is approximately 2 km ESE of the extended-Firth monitoring site.

Effects of acidification

- The respiration of organic matter generates CO_2 which decreases pH (acidification). Acidification can have detrimental effects on species such as shellfish, kina and coralline algae that use carbonate for their solid structures, particularly in the juvenile life stages. pH has also been shown to have an influence upon the behaviour/physiology of non-calcareous organisms.
- Continued monitoring is required to identify any trends in pH (our records are currently too short for trend testing).

Reversibility and remediation

- Since the total nitrogen load to the Firth is dominated by land-side nutrient inputs (at least when there is no strong ocean upwelling, which is the case for about 90% of the time) and nutrients fuel primary production, we expect that a reduction in land-side nutrient inputs will reduce the organic-matter load of the Firth and the consequent oxygen depletion that occurs in the extended Firth towards the end of the phytoplankton growth season (late summer to early autumn).
- However, we cannot make any quantitative predictions of what changes might ensue following any specific reduction in land-side nutrients until we have a more thorough understanding of the dynamics of the system.
- Without a return to the former sediment macrobenthic community a full recovery to the pre-catchment-development pattern of nutrient cycling and water quality in the Firth seems unlikely.

The data are not available to make a full assessment of water quality and ecosystem health. This report identifies gaps and priorities for future work that will enable more comprehensive assessments to be made in the future.

Introduction

Waikato Regional Council and DairyNZ share questions around water quality in the Firth of Thames. The questions relate to sediments, nutrients, phytoplankton/bacteria, dissolved oxygen and pH (acidification).

The objective of this report is to assess, where possible, the water quality and ecological health of the Firth of Thames, identify information gaps and recommend priorities for future work.

This report is complemented by a data report (Zeldis et al., 2015[1]) that describes the data that NIWA has collected in the Firth of Thames and Hauraki Gulf over the last 20 years.

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[1] Zeldis, J. et al. (2015) *Firth of Thames Water Quality and Ecosystem Health – Data Report*. NIWA Client Report No. CHC2014-123, prepared for Waikato Regional Council and DairyNZ.

1 Geographic zones

The Firth of Thames is a large mesotidal estuary on the east coast of the North Island (Figure 1-1). It is approximately 30 km long and 20 km wide, covering an area of about 730 km^2.

The extended Firth of Thames is an area of about 360 km^2 that is further north of the true Firth of Thames.

The Hauraki Gulf is the area north and west of the extended Firth of Thames. It contains the Waitemata Harbour, extending from Rodney in the west to the Coromandel Peninsula in the east.

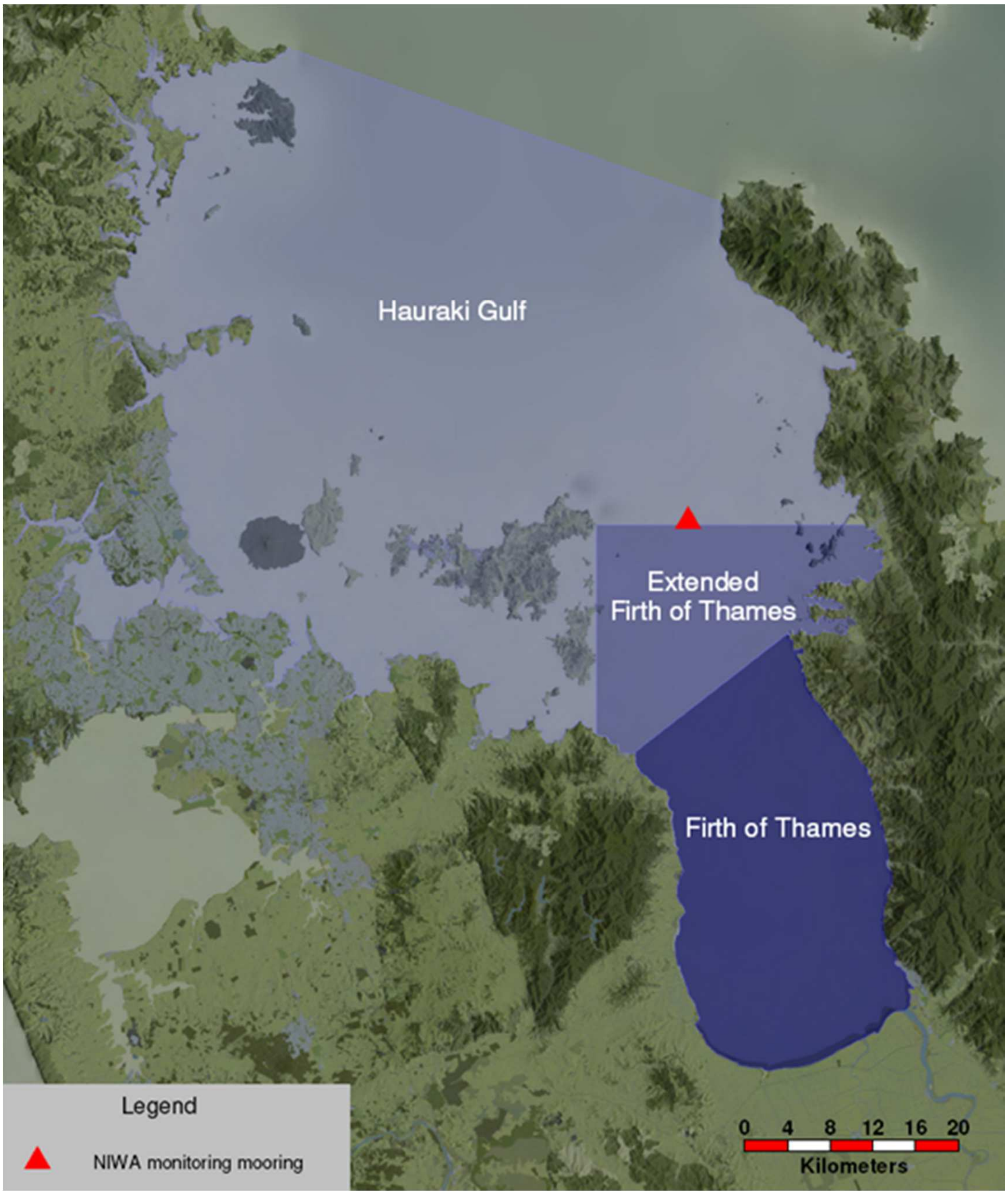

Figure 1-1: Geographic zones and place names. The red triangle shows the location of the extended-Firth monitoring site.

2 Physical setting

Water depth in the Firth of Thames increases from very shallow in the southern half (<5 m) to 40 m in its northern approaches (Figure 2-1). The wider Hauraki Gulf reaches a depth of about 60 m in the north, before extending to the continental shelf edge (>200 m depth).

The Firth of Thames drains a combined area of 4200 km^2, which comprises the three major river catchments of the Waihou River (1980 km^2 area), Piako River (1461 km^2) and Kauaeranga River (132 km^2). Approximately 65% of the 4200 km^2 total catchment is in pasture, and about 20% is in native bush. The catchments of the Piako and Waitoa Rivers are mostly covered in pasture (90%), and most of that pasture is used for dairy farming. Approximately 60,000 people live in the Hauraki rivers catchment.

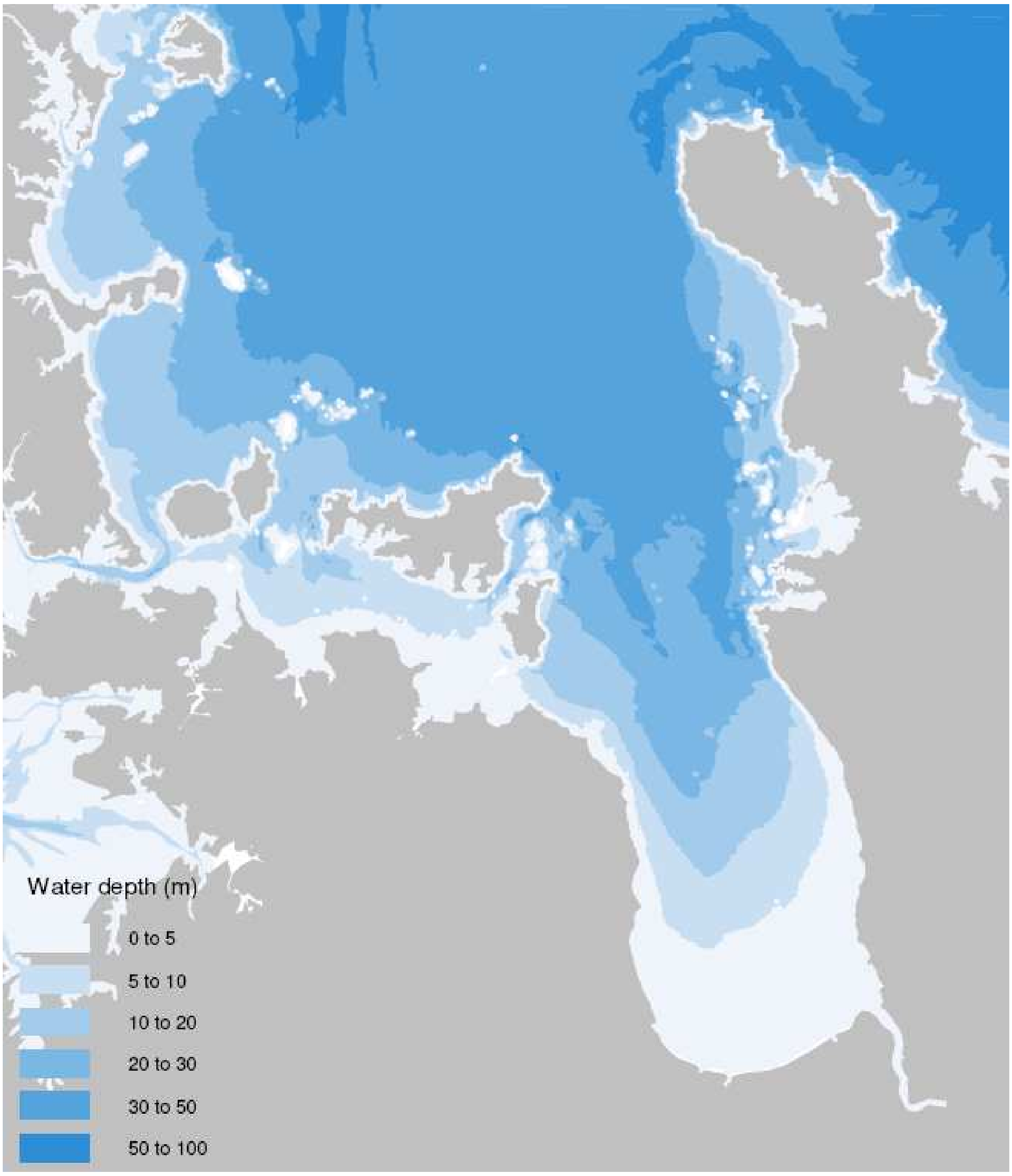

Figure 2-1: Bathymetry.

Prior to Māori and European land clearance, catchment landcover consisted of podocarp–hardwood forests on the Coromandel and Hunua Ranges. For much of the last 10,000 years, the Hauraki Plains have comprised freshwater marshes and swamp forests dominated by kahikatea, manuka and flax. Forest clearance by Maori was localised around settlements. European settlers arrived in the mid-1800s and large-scale deforestation began shortly after in the Coromandel Ranges, which was associated with timber logging and gold mining.

Early maps show that muds were accumulating in the Firth before large-scale catchment deforestation by European settlers had begun. Hydrographic surveys indicate that between 1882 and 1918 an estimated 7×10^6 m^3 of sediment was deposited within a 16 km^2 area of the lower Waihou River and its tidal delta and an estimated 37×10^6 m^3 was deposited in a 210 km^2 area of the Firth south of Tararu. Much of this sediment would have been associated with land clearance that preceded the development of pastoral agriculture in the Hauraki Plains. Prior to the construction of flood protection works following a large storm in 1938, floods deposited large quantities of sediment across the Hauraki Plains. Since the flood protection works, with floodwaters constrained to the river channels, sediment delivery to the Firth is likely to have been increased.

The Firth's tides are semi-diurnal with spring and neap tidal ranges of 3.2–3.5 m and 2.0–2.2 m, respectively. Northerly winds typically generate the largest waves, with periods less than 10 s and heights typically <1 m. Tidal currents may agitate bottom sediments and disperse suspended sediments.

The circulation of the open shelf adjacent to the Hauraki Gulf is strongly wind forced, which causes upwelling and downwelling (Figure 2-2). Upwelling is caused by persistent offshore (westerly) winds and brings cooler, nutrient-rich, low-oxygen oceanic water onto the shelf. Persistent onshore (northeasterly and easterly) winds cause downwelling, which transports nutrient-rich water away from the coast and depletes the continental shelf of nutrients. Upwelling is most frequent in winter and spring; downwelling in summer and autumn. During El Niño periods of the ENSO[2] weather cycle (indicated by a negative value of the Southern Oscillation Index, or SOI), westerly winds are more persistent (these reinforce upwelling of nutrient-rich, low-oxygen water). During La Niña periods of the ENSO weather cycle (indicated by a positive value of the SOI), northeasterly winds are more persistent (these reinforce downwelling).

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[2] El Niño Southern Oscillation.

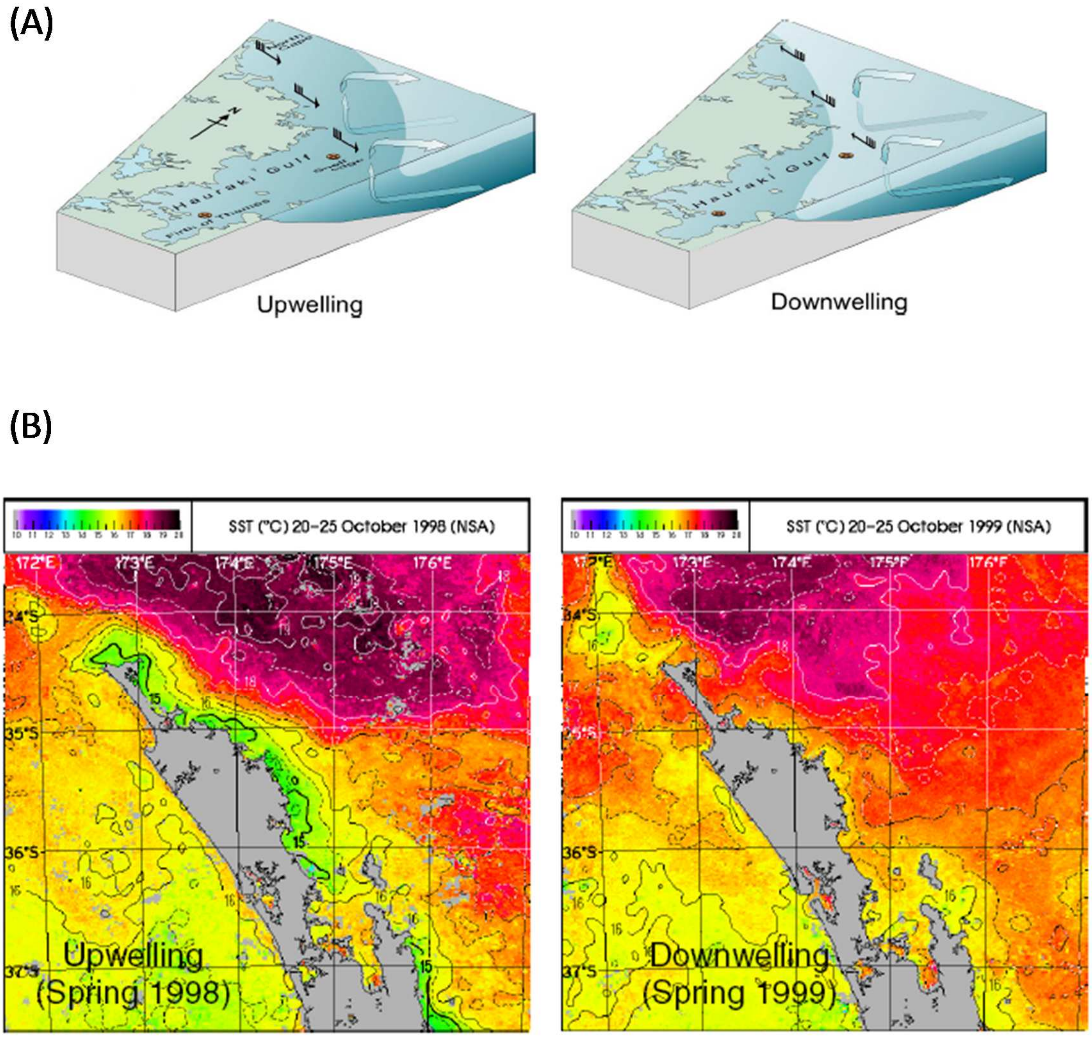

Figure 2-2: **Characteristics of upwelling and downwelling.**

3 Sediments

3.1 Sedimentation rates

Intertidal flats in the southern Firth have been accreting for the last 90 years at rates that are an order of magnitude greater (~25 mm y^{-1}) than rates that have been observed in intertidal regions of other North Island estuaries.

Sedimentation rates in subtidal areas of the southern Firth of Thames and in the extended Firth are much lower (2 mm y^{-1}) than on the intertidal flats, which we expect would be the case. However, this rate (2 mm y^{-1}) is much larger than rates obtained by Pocknall et al. (1989) from cores collected in water depths greater than 30 m in the extended Firth. Pocknall's cores gave sedimentation rates in the range 0.1–0.2 mm y^{-1} for the most recent interglacial, marine muddy fine sands that overlie early Holocene Last Glacial peats and coastal sediments (11,900–14,000 calendar years BP).

3.2 Mangrove expansion

Accumulation of mud has permitted widespread mangrove expansion, although this does not appear to occur continuously. Instead, successful mangrove recruitment – and therefore expansion – requires particular weather conditions, which only occur episodically.

3.3 Sediment budget

We have compared sedimentation rates to sediment inputs to develop a sediment budget (Table 3-1).

Table 3-1: Sediment budget for the southern Firth of Thames. Key: (1) Area per linear metre of shoreline; (2) SAR (m y^{-1}) is the present-decade average sedimentation rate ["SAR" stands for sediment accumulation rate or, more simply, just sedimentation rate]; (3) SAR (t y^{-1}) calculated per linear metre of shoreline using dry-bulk sediment density of 0.5 kg m^{-3}; (4) SAR-m is the total annual sediment-mass accumulation rate between the Piako and Waitakaruru Rivers (9.4 km); (5) SAR-m2 is the total annual sediment-mass accumulation rate in the Piako–Waitakaruru compartment per km^2.

Environment/ source	Compartment	Area (m^2)	SAR (m y^{-1})	SAR (t y^{-1})	SAR-m (t y^{-1})	SAR-m2 (t km^{-2} y^{-1})
Present day						
Mangrove forest	Old forest	260	0.01	1.3		
	Scrub forest	249	0.058	7.2		
	Fringe	116	0.056	3.3		
	Total-mangrove			11.8	110,900	18,860
Intertidal flat-1km	Upper intertidal	1000	0.025	12.5	117,500	12,500
Lower intertidal - subtidal flats	Area south of Tararu – Kaiaua	210 x10^6	0.002		200,000	1000
Waihou & Piako Rivers					190,000	–
Historical						
Southern Firth	as above (period 1882–1918)				18.3 x 10^6	2,427

Sedimentation rates indicate that ~110,000 t y^{-1} of fine sediment is accumulating in the mangrove forest and a similar amount is accumulating in the upper intertidal flat that is immediately adjacent (on the seaward side of the mangroves). By comparison, an estimated 200,000 t y^{-1} of fine sediment is accumulating in the 210 km^2 lower intertidal – shallow subtidal zone of the southern Firth. The present-day annual suspended-sediment loads of 160,000 t y^{-1} and 30,000 t y^{-1} for the Waihou and Piako Rivers, respectively, represent only about 40% of sediment depositing in the southern Firth. We think that the apparent discrepancy between sediment delivery by rivers and sedimentation in the Firth is due to the reworking by waves and currents of legacy sediments deposited in the Firth during large-scale deforestation and mining activities that occurred during the late 1800s to early 1900s. Under this scenario, intertidal flats are currently accreting legacy sediments that are being transported shoreward from the subtidal zone by waves and currents. WRC, DNZ and NIWA are currently researching this proposition.

3.4 Subtidal seabed sediments

Subtidal sediments have been mapped previously by Carter and Eade (1980), who depict the surficial sediments as being predominantly sandy muds (<0.063 mm grain diameter) and clays, with a minor coarse carbonate gravel (>2 mm) component (Figure 3-1).

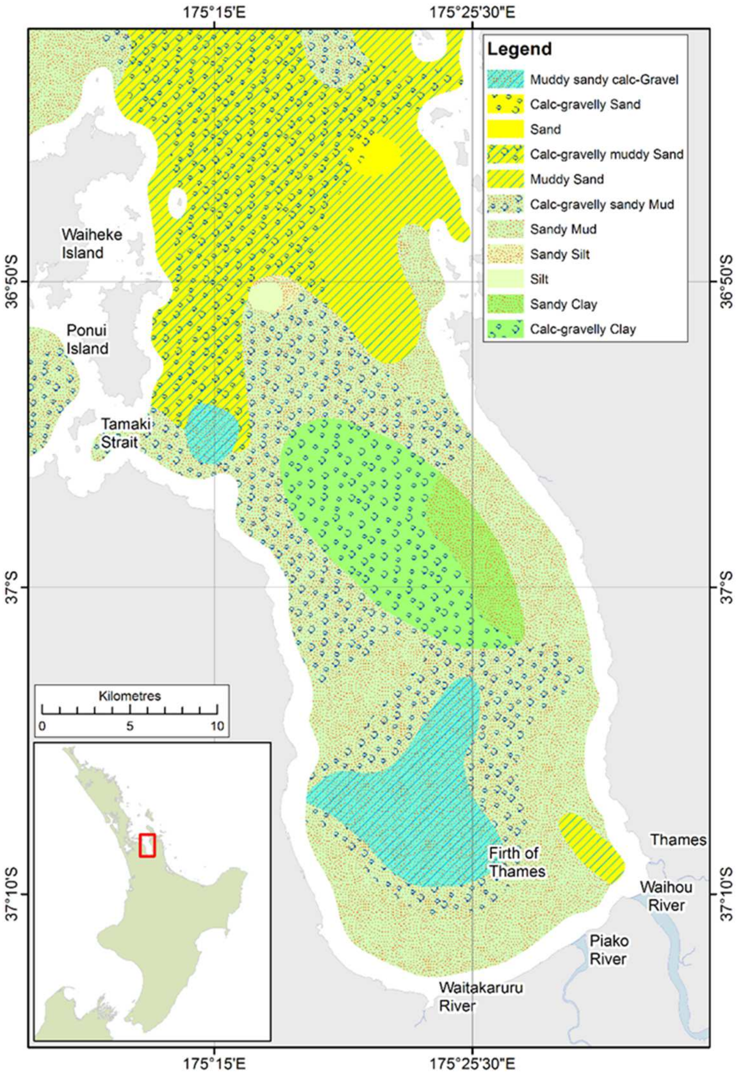

Figure 3-1: Carter and Eade's (1980) sediment map.

Our more recent data (voyages in 2002, 2003 and 2012) confirm that subtidal sediments in the Firth of Thames are very muddy (70–100 % mud), and moving from inshore to offshore sediments become sandier.

At one of our measurement sites in the extended Firth, the mud content of the seabed appears to have increased over the period 1999–2003. Data from 2012 suggest a continuation of that trend, but a change in analysis methods between 2003 and 2012 means we cannot be sure of that result. We do not have comparable data for other areas of the Firth so cannot extrapolate this result to other locations.

Subtidal seabed sediments are moderately rich in organic carbon, but nothing outstanding compared to other New Zealand estuaries.

3.5 Benthic fauna

Needham et al. (2014) provided a comprehensive review of monitoring over the past 10 years by Waikato Regional Council of the inner Firth’s intertidal benthic macrofauna and surface sediment. Needham et al. concluded there was no evidence of ecologically significant changes to either sediment characteristics or indicator taxa over the past 10 years of monitoring. We comment on that result below in section 3.7.

We have information on subtidal benthic infauna in the Firth and the extended Firth, but the data are limited, and do not tell us anything about trends. The data include information on bacteria (using phospholipids as a proxy), meiofauna and macrofauna abundance, chlorophyll *a* and associated pigments. The data suggest that the inner, subtidal Firth is depauperate in macrofauna and infauna relative to the central Firth. The most likely reason for this is that the inner Firth is muddier.

3.6 Numerical modelling

We have done numerical modelling to map dispersal of sediment discharged from river sources into the Firth. The modelling is limited in a couple of important ways: firstly, the sediment-transport model is not calibrated and, secondly, we have used the model to look at only a limited number of “scenarios” (different combinations of tide, wind and freshwater runoff).

The modelling shows that the three largest rivers (Waihou, Piako and Kauaeranga) deposit sediment in the southern Firth close to their respective mouths, with little river-borne sediment escaping from the entrance of the Firth to the wider Hauraki Gulf. Southwesterly winds steer sediment plumes along the western shore of the Coromandel Peninsula and northeasterly winds steer plumes along the southern and southwestern shores of the Firth.

3.7 Effects of sediments

The almost-complete collapse by the late 1960s of hard, biogenic reefs in the Firth composed of bivalves, sponges, ascidians, bryozoans and cnidarians has been well documented[3]. The reef collapse is likely to have reduced the overall biotic resilience and filtration capability of the Firth, and has

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[3] McLeod et al. (2012) ascribed the collapse of biogenic reefs in the Firth of Thames to dredge fishing from about 1910 to 1968 that removed extensive reefs of green-lipped mussels. They noted that, even though dredging never recommenced, the mussel reefs have not recovered. They investigated two potential reasons for this: (1) increased sedimentation and associated suspended sediments, which have a negative effect on the survival of mussels on the seafloor, (2) limited recruitment due to low larval supply or reduction in habitat that is suitable for larval settlement and post-larval survival. McLeod, I.M., Parsons, D.M., Morrison, M.A., Le Port, A., Taylor, R.B. (2012) Factors affecting the recovery of soft-sediment mussel reefs in the Firth of Thames, *New Zealand Marine and Freshwater Research*, 63: 78–83.

been accompanied by a shift in the sedimentary regime to an overall muddier system. **The modern sediment macrobenthic community of the Firth that has developed post-collapse under the muddier conditions is likely to be quite resilient.**

The monitoring reported by Needham et al. (2014), which showed little evidence of ecologically significant changes in intertidal benthic macrofauna over the past 10 years of monitoring, supports this view.

3.8 Reversibility and remediation

Even if catchment sediment inputs were to be turned off instantly, the prospects for a natural recovery of the Firth benthic ecosystem to a pre-reef-collapse state would be slim. If recovery were to occur, it is likely to be very slow.

We take this view because it is not likely that the Firth could “naturally” cleanse itself of the large sediment burden, even though internal transfers of legacy sediments are today occurring.

4 Overview – nutrients, phytoplankton, bacteria, dissolved oxygen and pH

In the remainder of this report we discuss nutrients, phytoplankton, bacteria, dissolved oxygen, and pH. The terms "autotrophy" and "heterotrophy" are defined in this section.

Phytoplankton[4] form the base of the planktonic foodweb. They use the energy from sunlight to synthesize simple sugars from dissolved inorganic carbon and water. As a side effect of this synthesis, free oxygen is liberated from the water molecules. The process of sunlight-driven sugar synthesis is known as "photosynthesis".

The sugars produced by photosynthesis are combined with dissolved inorganic nutrients (notably, nitrogen, phosphorus and, in some taxa, silicon) to build more complex molecules and entire cells. Overall, this net conversion of inorganic materials into organic material is called "autotrophy" or "primary production".

Phytoplankton growth tends to be restricted to the near-surface layers of the water column because light levels reduce with depth below the water surface.

Ultimately, much of the organic matter produced by photosynthesis sinks through the water column and is consumed (or "respired") by heterotrophic[5] organisms that include bacteria and zooplankton. When oxygen is present, respiration is "aerobic". Oxygen is consumed and carbon dioxide (CO_2) is liberated. In the marine environment, nitrogen in the substrate material is released as ammonium (NH_4^+), which may be oxidised to nitrate (NO_3^-).

Heterotrophic organisms draw oxygen from the pool of oxygen dissolved in the water column. If the heterotrophic drawdown of dissolved oxygen is greater than the combined rate of reoxygenation of the local water by diffusion from the overlying atmosphere and the rate of autotrophic production of oxygen then the dissolved oxygen in the local water will become "depleted".

Depletion of dissolved oxygen typically occurs at depth in the water column where atmospheric oxygen is slow to reach and low light levels limit autotrophic production (and associated oxygen generation). When the water column is density stratified, the situation is worse because the stratification inhibits the mixing and overturn of the water column. (Mixing and overturn help to reaerate the water column.) In these conditions, oxygen can reach levels that are low[6] enough to inhibit the activities of, or even harm, aerobic organisms. To remain healthy, more active and complex organisms (notably fish and decapods) tend to require higher oxygen concentrations than less complex/active ones.

When CO_2 is released into water it dissociates into carboxyl ions. In turn, these encourage the water molecules (H_2O) to dissociate into OH^- and H^+ ion pairs. Acidity (pH) is related to the hydrogen ion (H^+) concentration. Hence, aerobic respiration in water, which generates CO_2, will cause the water to become more acidic (that is, the pH will drop).

It is widely known that few organisms can withstand extremes of pH, but even small to moderate drops in pH can be harmful to some organisms. This is especially true of marine organisms that build

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[4] Phytoplankton, also known as microalgae, are microscopic marine plants. They contain chlorophyll and require light to grow.

[5] Heterotrophic organisms cannot manufacture their own food; in essence they eat autotrophic organisms.

[6] Hypoxia is a low level of oxygen; anoxia is no oxygen.

carbonate-based exoskeletons (molluscs, crustacean, corals, urchins, etc.) because carbonate tends to dissolve more readily as the pH drops.

There are two primary “external” sources of nutrients to the Firth. Firstly, upwelling of oceanic bottom water onto the coastal shelf (that occurs during prolonged periods of offshore [westerly] winds) brings cooler, low-oxygen, naturally nutrient-rich water into the Firth[7]. Secondly, freshwater runoff provides nutrients from the land to the coastal zone.

Nitrogen is typically the limiting nutrient in coastal marine waters, hence, excessive nitrogen in the water column can stimulate excessive organic matter production by autotrophs (i.e., phytoplankton). Subsequent decay of this locally produced organic material (together with decay of any organic material exported from the catchment) can induce oxygen depletion, with subsequent adverse effects on aerobic animals including fish and shellfish. Respiration of organic matter also produces CO_2, which can acidify the water, with adverse effects on creatures that build shells. This combination of nutrient enrichment and associated “symptoms” or adverse effects is called “eutrophication”. Systems which have long flushing times (that is, limited or slow exchange of water with more pristine waters[8]) are more prone to eutrophication than well-flushed systems.

In healthy coastal ecosystems, any tendency towards eutrophication is countered by denitrification, which converts nitrate to gaseous N_2 (mainly in the sediments). The N_2 can then bubble to the sea surface and be vented to the atmosphere. Gaseous N_2 cannot be used as a nutrient by most autotrophs so, effectively, it is lost from the productive system.

Denitrification is driven by microbial processes at the oxic/suboxic boundary in the seabed sediments. Strictly, denitrification is the conversion of nitrate (NO_3^-) into free N_2, which occurs under anoxic conditions. The standing pool of NO_3^- is usually small and, if it were not replenished, rates of denitrification would quickly fall to zero.

Under aerobic conditions NH_4^+ (ammonium, which is often an end-product of respiration – see above) is converted to NO_3^- by specific bacteria. Therefore, successful conversion of ammoniacal nitrogen into free N_2 requires that aerobic and anaerobic processes occur in close proximity to one another, such that NO_3^- formed in the aerobic region can quickly move into the anaerobic zone where it may transform into N_2.

Hypoxia suppresses conversion of ammonium to NO_3^- and tends to increase the distance between aerobic and anaerobic zones, thus suppressing denitrification. Thus, hypoxia promotes retention of nitrogen in bioavailable forms (ammonium and nitrate) that are available to autotrophs. This leads to a positive feedback loop whereby the retained nitrogen fuels further production of organic matter, which fuels oxygen depletion, which suppresses denitrification, and so on.

Denitrification can thus be viewed as a valuable ecosystem service provided by coastal waters.

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[7] Winds during winter and spring tend to blow more from the west than normal during El Niño phases of the Southern Oscillation; during La Niña phases winds tend to be northeasterly, which drives downwelling that in turn transports warmer shelf waters onshore.

[8] In this context, a “long flushing time” is likely to be around 10 days or greater.

5 Nutrients

5.1 Data

Nutrients were sampled at the extended-Firth monitoring site (the “Firth” in Figure 5-1) at 3-monthly intervals over the 15-year period 1998 to 2013. At the same time, phytoplankton and bacteria, dissolved oxygen and pH were measured, which we discuss in following sections.

Samples were collected by lowering a CTD that contained a sampling rosette (Figure 5-1) from a research vessel (usually the R/V *Kaharoa*, operated by NIWA). Typically, samples were collected at 6 depths in the water column. (These same samples were analysed for phytoplankton and bacteria.)

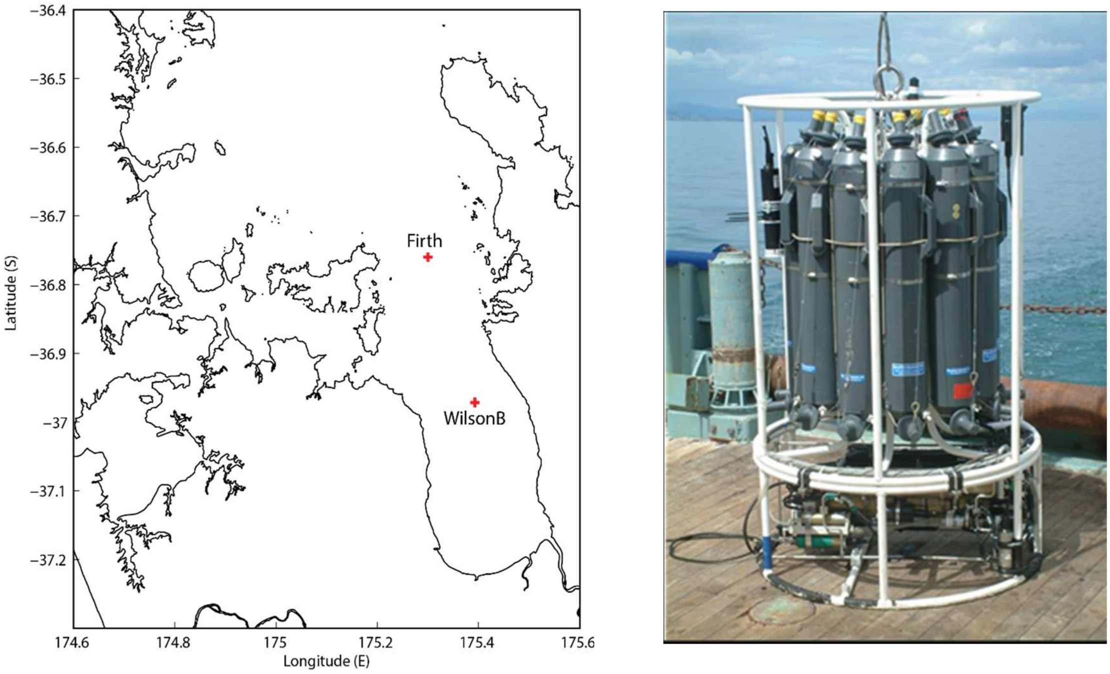

Figure 5-1: (Left) Location of the extended-Firth monitoring site ("Firth" in the figure) and the Wilson B mooring site. The extended-Firth monitoring site is at 36^0 45.6′ S, 175^0 18.0′ E. The water depth is 40 m. The Wilson B site is adjacent to the Wilson Area B Marine Farm Zone (36^0 58.297′ S, 175^0 24.116′ E; 16 m depth). **(Right) The Conductivity–Temperature–Depth (CTD) instrument about to be deployed from the stern of NIWA RV *Kaharoa*.** The CTD is lowered though the water and used to sample parameters including temperature, salinity, oxygen and light, at various depths in the water column, using the electronic sensors at the base of the package. The bottles can be shut at specified depths to capture water for later laboratory analysis for nutrients and phytoplankton.

Some of the data are shown in Figure 5-2.

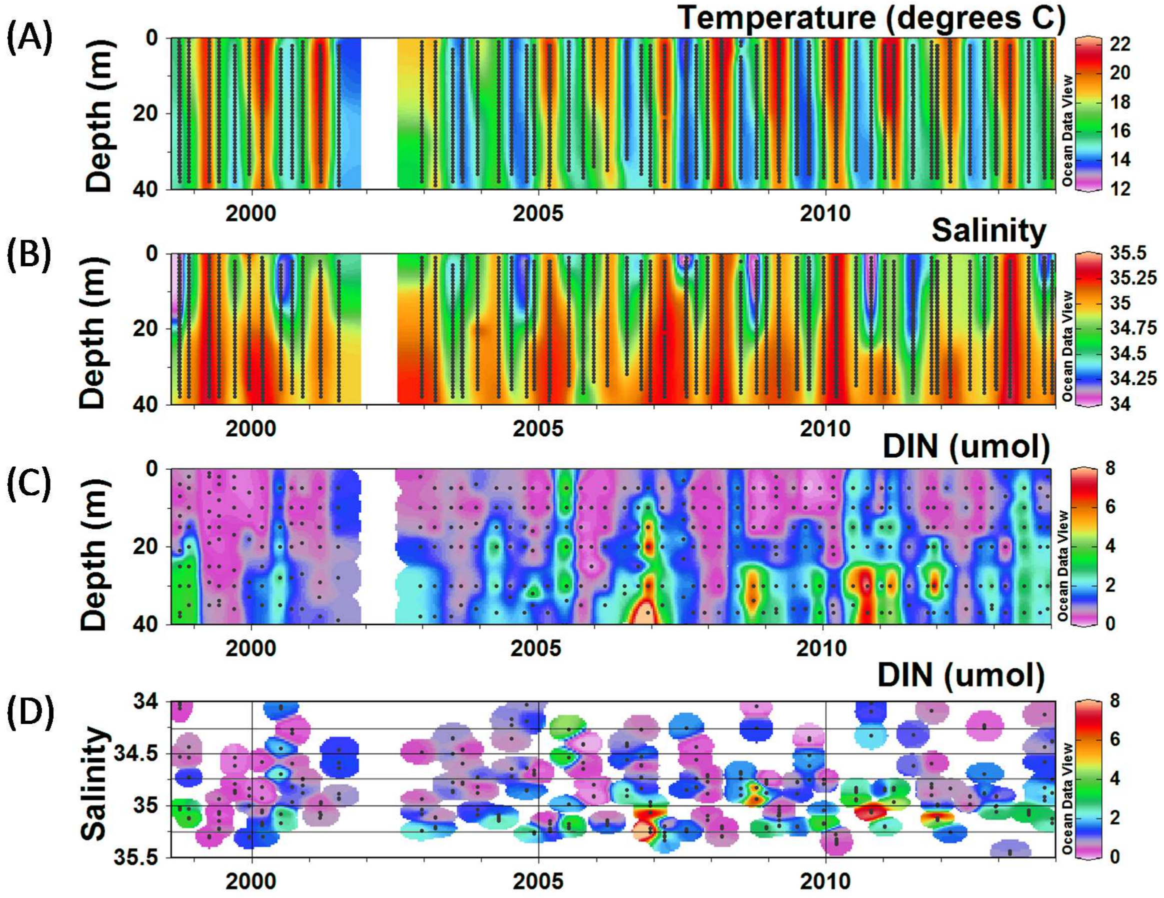

Figure 5-2: 15-year time series of nutrients (dissolved inorganic nitrogen), temperature and salinity at the extended-Firth monitoring site.

The 15-year measurements of the different nutrient species reveal that dissolved inorganic nitrogen (DIN; the sum of nitrate and ammonium) is often most abundant in the upper water column during winter and early spring (indicated by times when temperatures are low: Figure 5-2A). The most likely reason is that uptake of DIN by primary production is limited by low light at those times. In summer and autumn, when there is plenty of light and seasonal production is well-developed, DIN in the upper water column is reduced because of uptake by primary production.

5.2 Trends

We conducted trend analysis on the nutrient data after integrating it over depth in the water column. We used the non-parametric seasonal Kendall trend test[9] to detect trends in the water-column-integrated data. The water-column-integrated DIN concentration is shown as a time series in Figure 5-3, and the results of the trend analysis are tabulated in Appendix A.

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[9] The seasonal Kendall trend test tests for a monotonic trend in data. It is a nonparametric test, meaning that data are not required to be normally distributed for the test to be valid. “Monotonic” means the data consistently increase or decrease over time. Any trend may or may not be linear. “Seasonality” implies that the data are differently distributed in different seasons. A “season” may or may not be a season in the normally understood sense; for example, three 8-hour periods in a day may constitute different seasons. In our analyses, “season” really does mean a traditional calendar season.

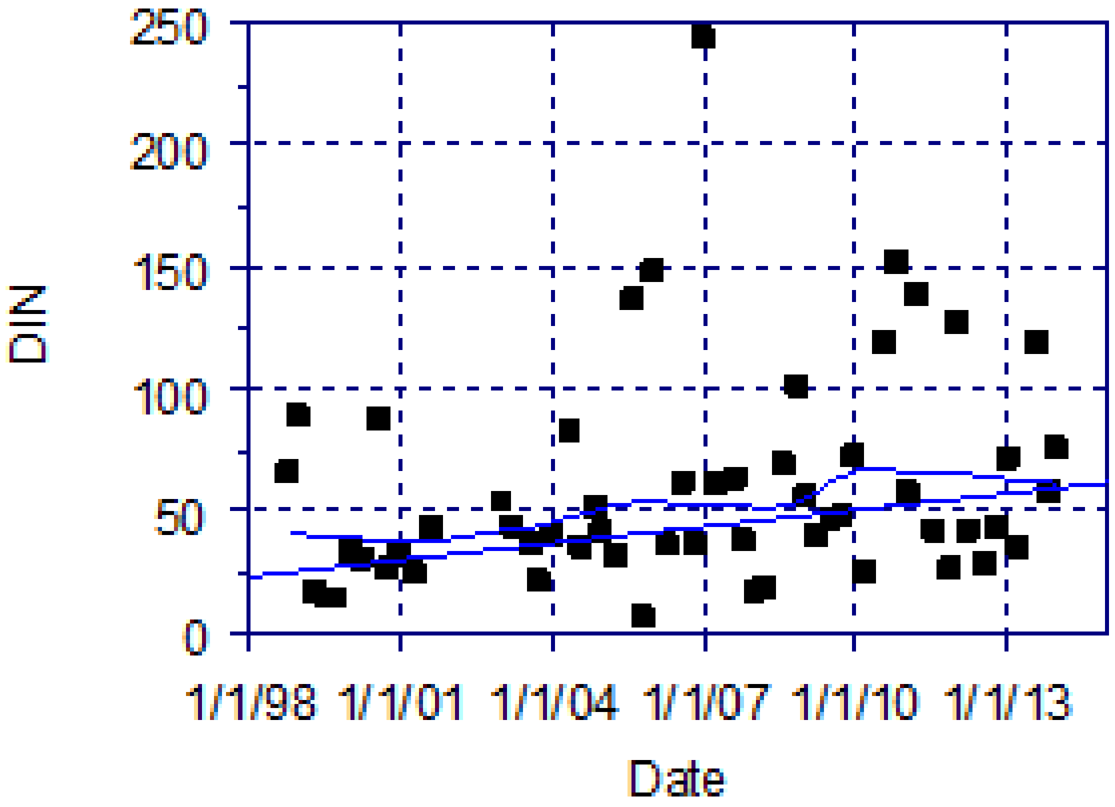

Figure 5-3: Time series of water-column-integrated DIN concentration (units of mg m^{-3}) at the extended-Firth monitoring site. Note that 1 µmol L^{-1} DIN = 14 mg m^{-3} DIN. The blue curves show the fitted linear Kendall trend (the straight line) and a LOWESS moving average fit (the other line) that used 40% of the points in its fitting window.

The seasonal Kendall trend tests revealed:

- DIN had increased at a rate of 5.1% y^{-1} over the 15-year measurement period. This was a statistically significant[10] result ($p < 0.05$).
- Dissolved organic nitrogen (DON) was abundant relative to DIN, and also had a significant increasing trend (1.8% y^{-1}).
- In contrast, dissolved inorganic phosphorus (DIP) did not change significantly.
- Dissolved organic phosphorus (DOP) was less abundant relative to DIP, and decreased at a statistically significant rate of -5.5% y^{-1}.
- The ratio DIN/DIP increased at a statistically significant rate of 4.2% y^{-1}, indicating enrichment of N in the system relative to P.

These results are for water-column-integrated data and therefore represent the entire inventory of each dissolved nutrient at the extended-Firth monitoring site through time.

We have looked at what factors might be driving an increase in nitrogen at the extended-Firth monitoring site over the 15-year measurement period. The possible factors that we looked at divide

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[10] This is statistical significance ($p < 0.05$), not that it necessarily has any particular or significant implication.

broadly into two types: changes in oceanographic conditions, and changes in nutrient runoff from the land.

- There does not appear to have been a sufficient upward trend in nutrient runoff from the Waihou River to fully explain the upward trend in nitrogen at the extended-Firth monitoring site, as follows.

  Trends in river water quality in the Waikato region since 1993 have been described by Vant (2011) and Vant (2013). Many (67%) of the records showed no “important” trends, while 18% of the records showed improvements and 15% showed deteriorations.

  Vant (2013) gave trends for the Coromandel and Hauraki rivers, including patterns in the Waihou and Piako Rivers, which dominate riverine nutrient inputs to the Firth. For TP, improvements were found at most sites in both rivers. For TN, minor improvements or no change were found in the Piako River and deteriorations were found in the Waihou River.

  The Waihou River[11] showed flow-adjusted TN increasing at rates of 0.5, 1.0 and 1.7% y^{-1} at 3 monitoring sites, the latter two of which were considered to be “important”. However, these rates are considerably less than the DIN trend that we see in the marine record. Furthermore, the site furthest downstream on the Waihou River, which we can reasonably expect to be most indicative of the loading into the Firth, actually had the slowest increase (0.5% y^{-1}) in TN. However, since DIN is just one component of TN, then if all of that 0.5% y^{-1} increase in TN at the site furthest downstream has occurred as an increase in DIN, then the % increase in DIN will actually exceed 0.5%. This needs to be explored.

  The Coromandel rivers contribute much lower nutrient loads and showed “important” increases for TN in the Kauaeranga (3.3% y^{-1}) and, for the Ohinemuri, no change at 2 sites and an “important” increase at one site (1.2% y^{-1}).

  To provide a more nuanced view on whether there are trends in nutrient runoff that could match the trend we have found in water-column-integrated DIN, the analysis of river loads should be repeated with a focus on “terminal reach” (i.e., at the location just before the river debouches at the coast) loads. Also, river trends in DIN, in addition to trends TN, need to be considered and understood.

- We have analysed the Southern Oscillation Index to see whether the upwelling regime may have changed (upwelling, driven by westerly winds, brings cool, nutrient-laden oceanic water onto the shelf). However, we found no significant shift in the SOI over the 15-year period. (The results are tabulated in Appendix A.) Satellite remotely-sensed sea-surface temperature data for the shelf north of the Gulf dating from 2003 also did not exhibit any long-term cooling trend, which could have resulted from a change in the upwelling regime.

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[11] Which, we estimate, via the budget shown in section 10, supplies about 60% of the total nutrient load to the Firth.

Further analyses need to be done on measurements of salinity and water temperature above and below the pycnocline[12], which could result from changed oceanographic conditions.

We view the seasonal Kendall trend test of the water-column-integrated data as a first step towards identifying and understanding trends. The nutrient data exhibit significant vertical structure over the water column (see Figure 5-2), that is, the water chemistry is markedly different between top and bottom water, which is lost by depth-integrating the data.

- For example, simple visual inspection of panel C in Figure 5-2 suggests that DIN has mostly changed in the water column at levels below about 20 m below the water surface. Furthermore, the change in DIN in the lower water column appears to have been driven by stronger “pulses” of DIN occurring later in the monitoring period. (Analysis is required to verify both of these casual observations.) This kind of detail, which may be important, is lost in the analysis of the water-column-integrated data.

One other possibility as a driver of the water-column-integrated DIN trend is that there has been a change in the way the seabed “processes” nitrogen, which could have resulted in a redistribution of nutrients across the various sediment, water and phytoplankton “compartments” that comprise the system. We talk further about this possibility in section 11.3 where we discuss trends.

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[12] The layer in the water column where the density gradient is greatest. Many properties of ocean water above and below a narrow pycnocline can be quite different.

6 Phytoplankton and bacteria

6.1 Data

Our data show that there are more phytoplankton in the Firth of Thames than in the extended Firth of Thames (Figure 6-1). Both of these areas contain more phytoplankton than the wider Hauraki Gulf. Rates of primary production (expressed as carbon fixed per time per area) follow a similar pattern (Figure 6-2).

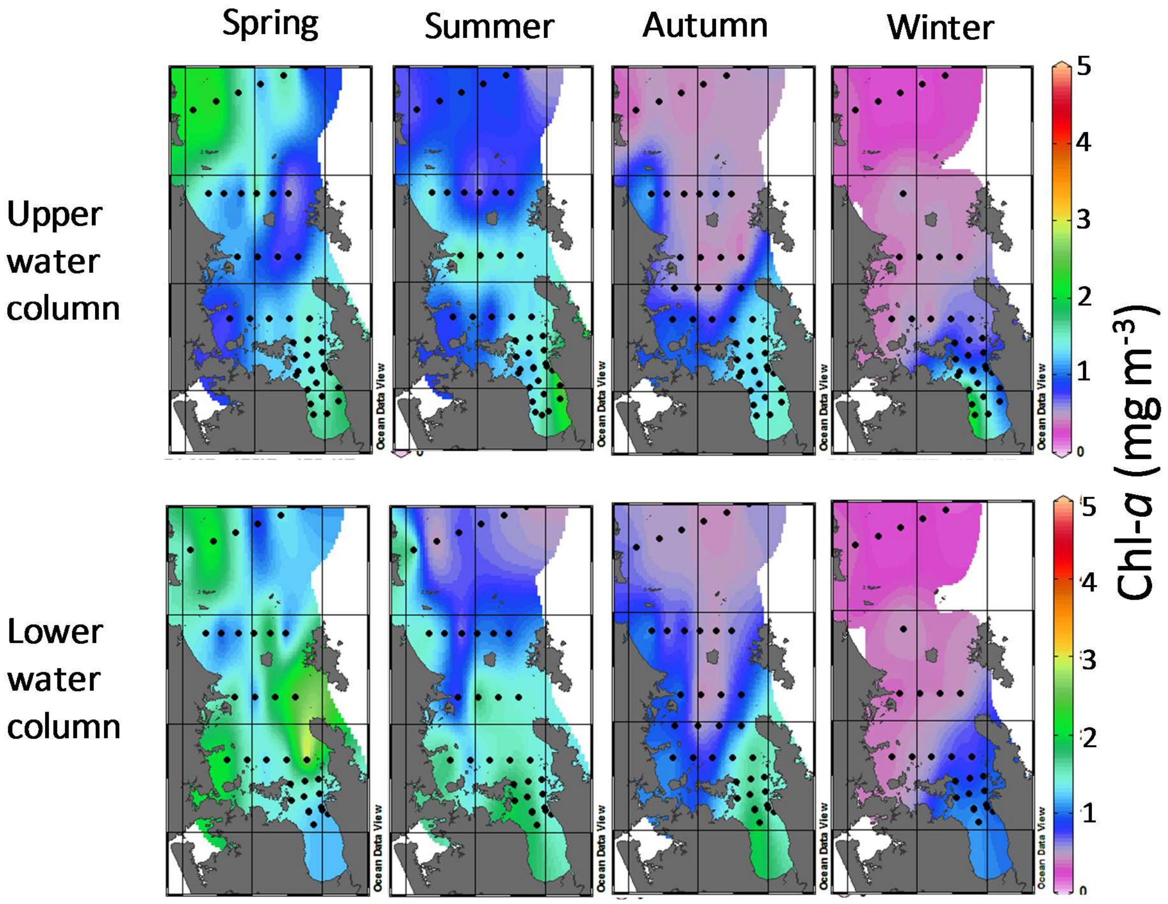

Figure 6-1: Seasonal phytoplankton distributions in spring, summer, autumn and winter. Chlorophyll *a* data were compiled from NIWA voyages made between 1996 and 2012. Values are averages for the upper water column (upper 15 m) and the lower water column (16–50 m), with sampling sites shown by black dots. Note that the inner Firth is shallower than 15 m hence no lower water column values were estimated.

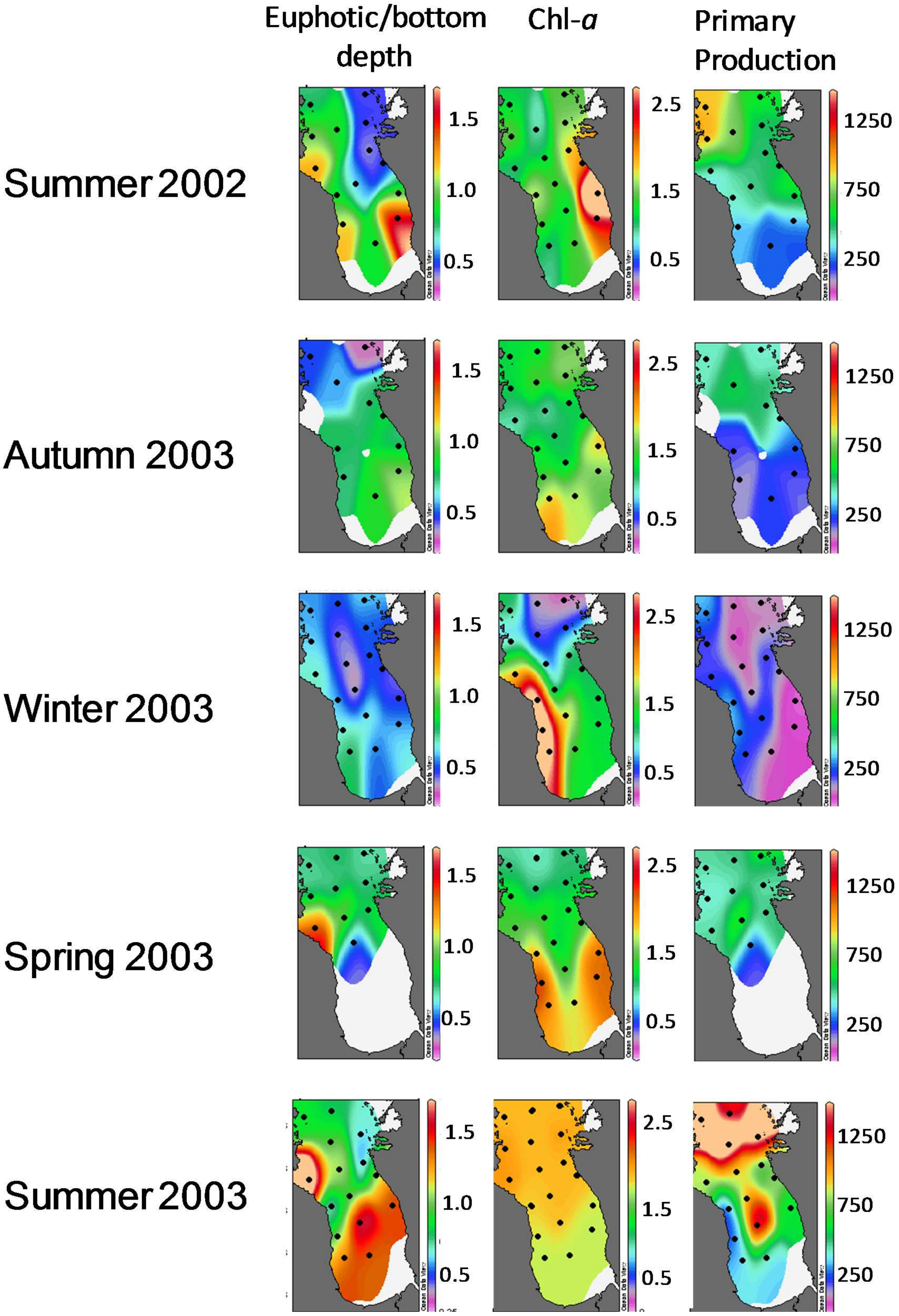

Figure 6-2: Primary production in Firth over 5 seasonal voyages, summer 2002–summer 2003. The columns show (left to right) the depth of light penetration (euphotic depth) relative to bottom depth, depth-integrated chlorophyll *a* concentration (mg m^{-2}) and primary production rate (mg C m^{-2} d^{-1}). Some light penetration data were lost in the spring voyage. The euphotic depth is the depth below the water surface where light first reaches 1% of the value incident at the water surface.

Figure 6-1, which is compiled from data collected during voyages made between 1996 and 2012, shows that phytoplankton biomass varies seasonally, being generally greatest in spring and least in winter. Biomass is widely distributed in spring, but becomes progressively restricted to inshore areas (especially the Firth) from summer through winter. In the outer Firth, biomass is greatest in the upper water column in spring, but increases noticeably at depth in autumn.

Seasonal variation in primary productivity has a great bearing on standing stocks of nutrients. Spatial surveys of the Firth in spring, summer, autumn and winter of 2003 and during 2012–13 (see Figure 6-2 and Figure 6-3) showed that phytoplankton growth reduced nitrate to low levels in all seasons except winter, while ammonium mineralisation[13] was evident in summer and autumn. It is in winter, when production is strongly light-limited (see primary production [pp] values in Figure 6-3), that the "conservative" spatial pattern of nutrients becomes evident. This is characterised by a gradient in nitrate concentrations, decreasing towards offshore from the inner Firth. **This suggests that catchment loading dominates DIN stocks.** We examine this suggestion in section 10 where we develop a budget for carbon/nutrients.

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[13] "Mineralisation" is the breakdown by living organisms of organic matter into inorganic substances.

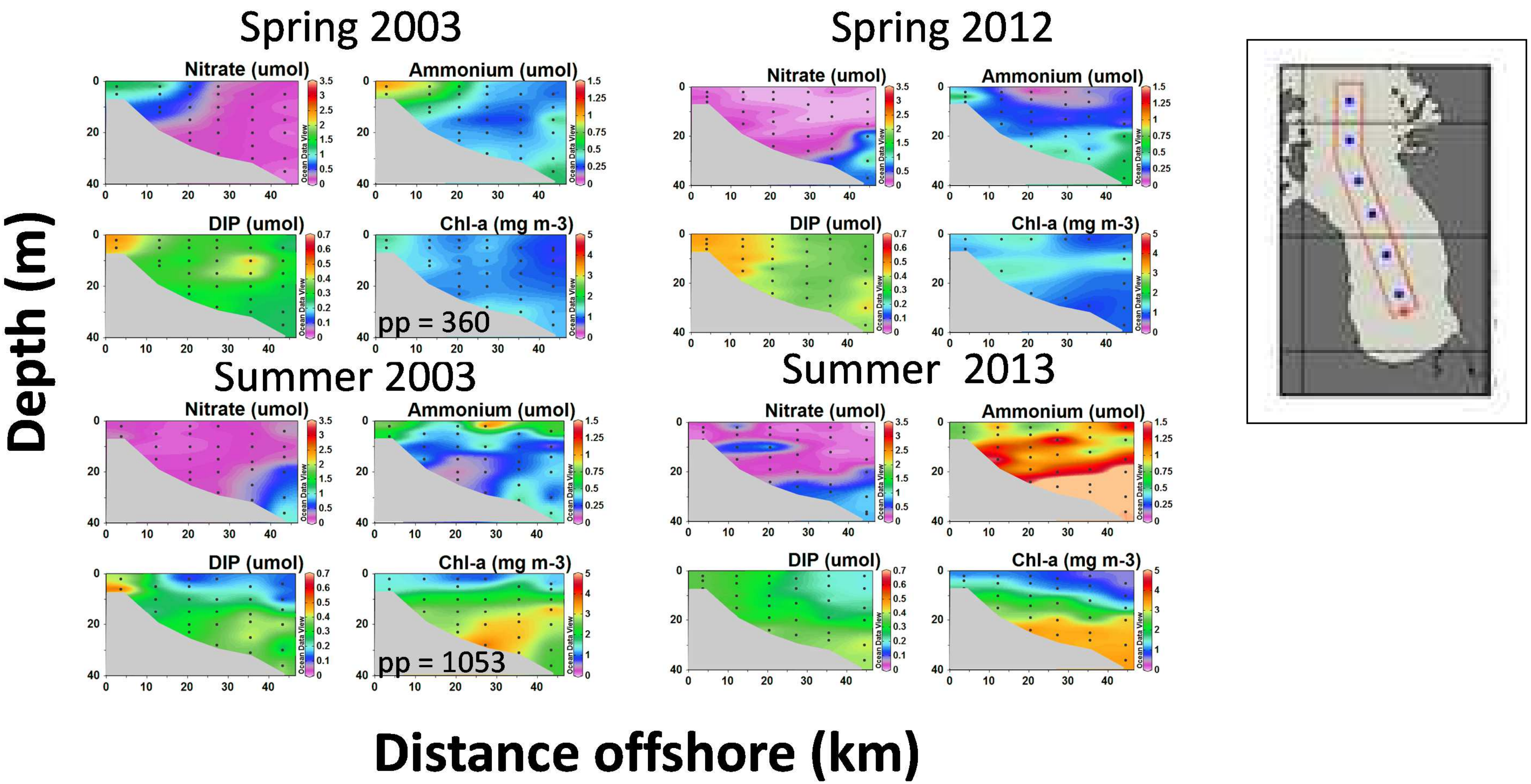

Figure 6-3: Transects of nutrient and chlorophyll a concentration from the inner Firth to the outer Firth (inset), by depth and season during seasonal voyages made in 2003 and 2012–13. Rates of primary production averaged across the Firth ("pp": mg C fixed m^{-2} d^{-1}) during the 2003 surveys are annotated on the 2003 chlorophyll *a* plots. **<u>This page</u>: spring and summer. <u>Next page</u>: autumn and winter.**

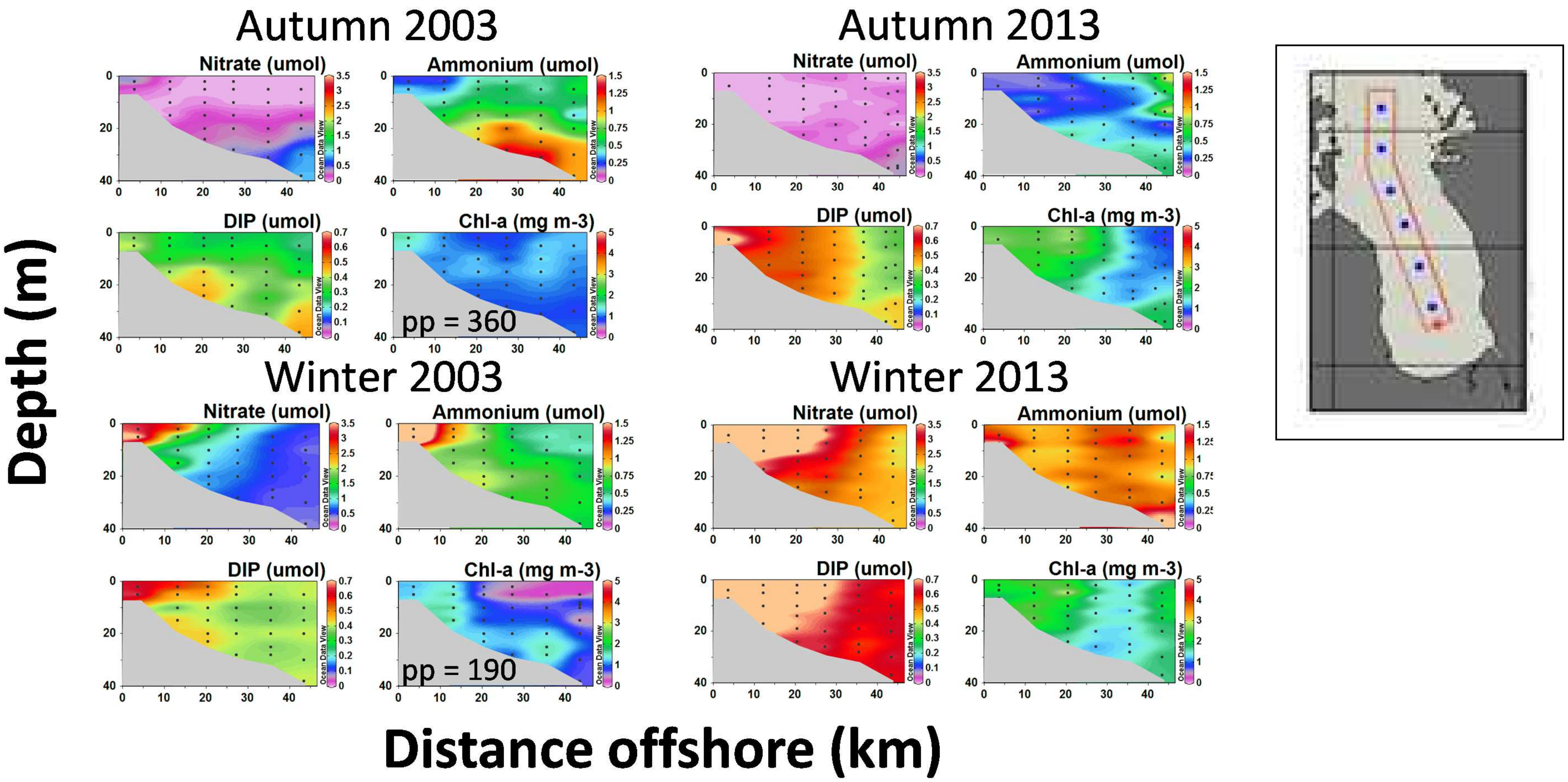

Figure 6-3: Transects of nutrient and chlorophyll a concentration from the inner Firth to the outer Firth (inset), by depth and season during seasonal voyages made in 2003 and 2012–13. Rates of primary production averaged across the Firth (“pp”: mg C fixed m^{-2} d^{-1}) during the 2003 surveys are annotated on the 2003 chlorophyll *a* plots. **<u>This page</u>: autumn and winter. <u>Previous page</u>: spring and summer.**

6.2 Trends

Phytoplankton pigment (chlorophyll *a* and phaeopigment[14]) and microphytoplankton cells (>2 µm cell size) have been sampled at the extended-Firth monitoring site at a 3-monthly interval over the 15-year period 1998 to 2013. The samples were collected by lowering a CTD-rosette from a research vessel. Typically samples were collected at 6 depths in the water column (these same samples were analysed for nutrients).

Plots of chlorophyll *a* and its breakdown product, phaeopigment, suggest increasing concentrations in the lower half of the water column over the 15-year measurement period (Figure 6-4).

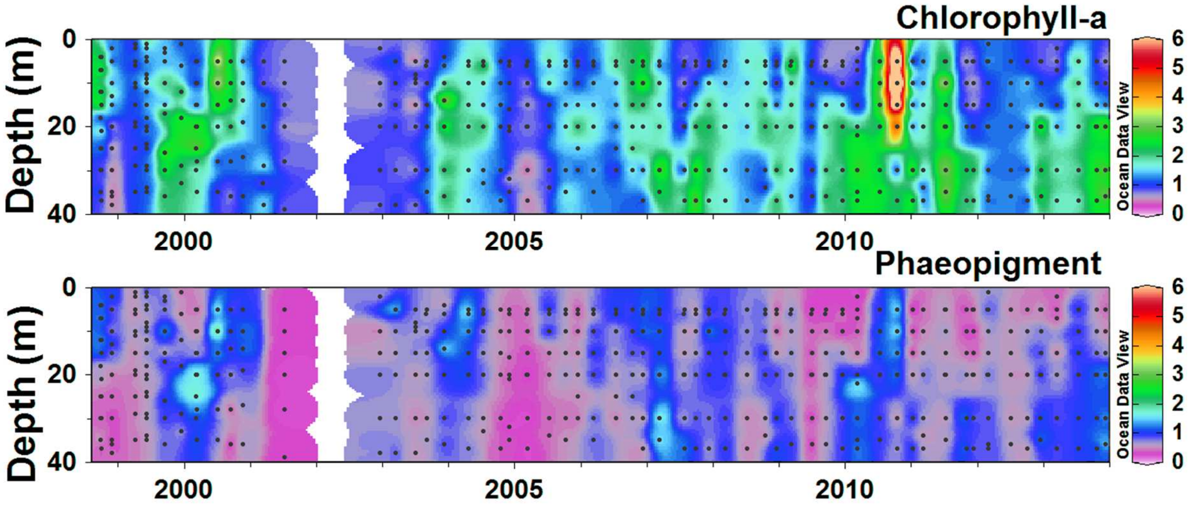

Figure 6-4: Phytoplankton pigment concentrations (mg m^{-3}) plotted against depth below the water surface and time at the extended-Firth monitoring site.

We subjected the phytoplankton data to the seasonal Kendall trend test. For these tests, we divided some of data into two depth bins: from the water surface to 20 m below the surface (the "upper water column"), and from 20 m below the surface to 40 m below the surface (the "lower water column")[15]. This included the chlorophyll *a* and phaeopigment data. For other data, including cell counts and biomasses of different taxonomic groups, we analysed water-column-integrated data.

The results of the trend tests are tabulated in Appendix A. The results show a number of trends at the extended-Firth monitoring site over the 15-year measurement period.

- Chlorophyll *a* concentration and phaeopigment in the lower water column increased over the 15-year monitoring period. Chlorophyll *a* increased by about 4.2% y^{-1} and phaeopigment by about 2.5% y^{-1}. These were statistically significant increases.
- There was no trend for chlorophyll *a* or phaeopigment in the upper water column. This result has also been observed in monitoring data from Wilson Bay Area A (Stenton-Dozey and Zeldis, 2014) and is consistent with upper-water-column fluorometer data that we have collected.

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[14] Phaeopigment is a product of the breakdown of chlorophyll *a*.

[15] These correspond to, roughly, above and below the pycnocline.

- Cell counts (integrated over the water column) of total microphytoplankton showed a significant increasing trend of 6.9% y^{-1} over the 15-year monitoring period (Figure 6-5). Total microphytoplankton comprises diatoms, dinoflagellates and "others" (a miscellaneous group of mostly small phytoplankton). Still in terms of cell numbers, the largest increases were in diatoms (4.6% y^{-1}) and others (6.7% y^{-1}). The cell numbers of large centric diatoms (which is a subgroup of diatoms) increased by 8.9% y^{-1}. All of these trends were statistically significant. Cell numbers of dinoflagellates showed a non-significant decreasing trend.

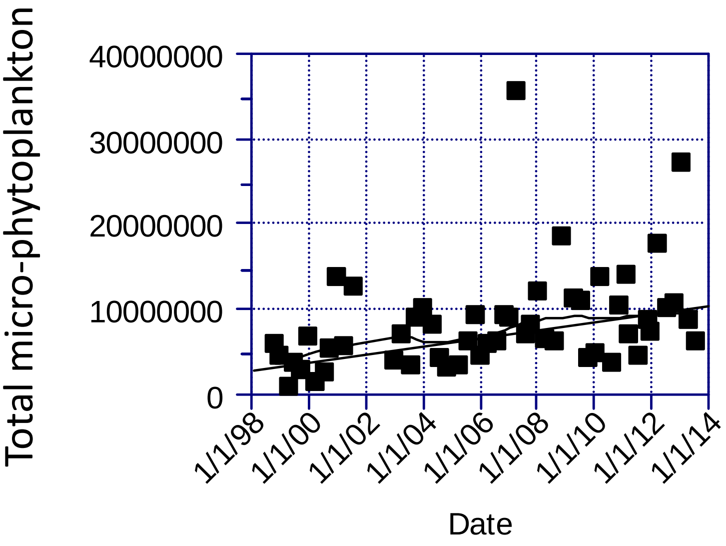

Figure 6-5: Time series of water-column-integrated total microphytoplankton cell counts (cells m^{-2} x 10^{-3}) at the extended-Firth monitoring site. The blue curves show the fitted linear Kendall trend (the straight line) and a LOWESS moving average fit (the other line) that used 40% of the points in its fitting window.

- Biomass of total microphytoplankton (integrated over the water column) increased by 2.5% y^{-1} over the 15-year monitoring period (Figure 6-6), however, this trend was not statistically significant at the 95% confidence level. (The trend had an associated *p* value of 0.07, whereas $p < 0.05$ is considered to be statistically significant.)[16] The following group trends were statistically significant: the bacteria group (7.0% y^{-1}, on a relatively high biomass), the "others" group (6.0% y^{-1}, on a relatively moderate biomass), and the prokaryotic picophytoplankton group (12.3% y^{-1}, on a relatively low biomass).

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[16] The raw data that we have to work with are cell counts, and we convert these to biomass by assuming a certain biovolume per cell. This can lead to loss of precision in the data. For instance, we adjusted the assumed biovolume per cell through time from 1998–2013 depending on observed biovolume changes within taxa, which can occur as a consequence of maturity of the population, stage of growth cycle, etc. However, because it was impractical to make the conversion adjustments on every taxon for every sample, scope for error was introduced if the conversions were applied inappropriately through time. The effects of these errors can be substantial because the conversions generally involve cubic functions of cell dimensions.

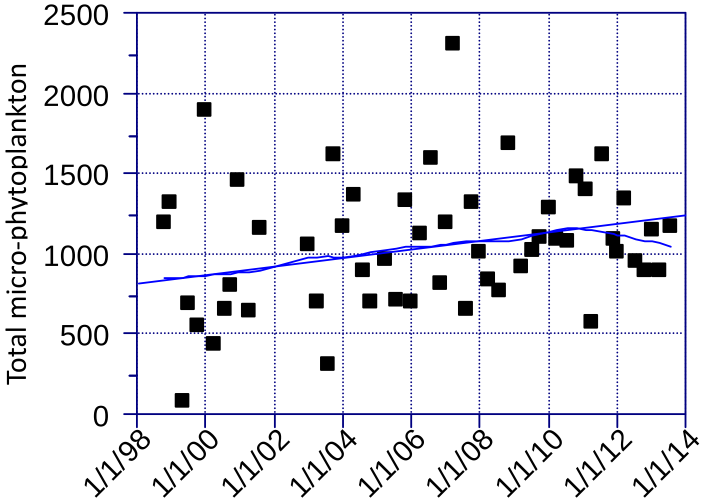

Figure 6-6: Time series of water-column-integrated total microphytoplankton biomass at the extended-Firth monitoring site. The blue curves show the fitted linear Kendall trend (the straight line) and a LOWESS moving average fit (the other line) that used 40% of the points in its fitting window.

The overall changes to total microphytoplankton over the 15-year monitoring period are consistent with what might be anticipated if nutrients have become more abundant.

We looked for trends in toxin-producing phytoplankton counts and biomass.

- Potentially toxic genera were broken down into three groups; dinoflagellates, diatoms, and "others". The toxic dinoflagellates included the more prominent genera *Karenia*, *Alexandrium*, *Dinophysis*, *Gonyaulax*, *Lingulodinium*, and the less common *Ostreopsis* and *Gambierdiscus*. Toxic diatoms were limited to the genus *Pseudo-nitzschia*, which is capable of dominating the entire phytoplankton population at times. The toxic "others" group consisted of the raphidophytes including *Heterosigma*, *Fibrocapsa* and *Chattonella* as well as the occasionally observed *Oscillatoria*/*Trichodesmium* and *Prymnesium*.
- The only group to show a significant trend was toxic diatoms (11.3% y^{-1} increase in cell numbers), which was driven by an increase in numbers of *Pseudo-nitzschia*. However, toxic diatom biomass did not change, and neither did *Pseudo-nitzschia* biomass. This implies there was a shift to more numerous but smaller toxic diatom cells.
- *Pseudo-nitzschia* biomass makes up a small fraction of the total microphytoplankton biomass.

7 Dissolved oxygen

7.1 Data

Our primary datasets vis-à-vis dissolved oxygen (DO) derive from:

- 15 years of measurements made seasonally (every 3 months) over the period 1998–2013 at the extended-Firth monitoring site (Figure 5-1). The measurements were made using a CTD deployed from a research vessel. During this same sampling programme we were measuring nutrients and phytoplankton (reported in previous sections).
- Various spatial surveys using a CTD deployed from a research vessel.
- Moored dissolved-oxygen sensors at the extended-Firth monitoring site and at the Wilson B site, which is 25 km to the south (Figure 5-1). At both of these sites, sensors measured DO every 15 minutes.
  - The data at the extended-Firth monitoring site were collected with DO sensors mounted in the upper and lower water column at mean depths below the water surface of 10 and 33 m. Measurements were made over the period 2005–2014.
  - The Wilson B data, which were collected using a Seabird IDO MicroCAT at 5 m below the water surface, are from the period January to April, 2013[17].

7.2 Patterns in DO

Whilst we have long time series of DO at one site, we have fewer data from other sites. **Thus, we cannot make conclusive statements about the oxygen status of the entire region.** Nonetheless, the data do reveal temporal and spatial patterns, in particular, of occurrences of low dissolved oxygen in the water column.

Figure 7-1 shows temporal patterns in DO, temperature and water-column stratification at the extended-Firth monitoring site during the period 1998–2013. The data underlying Figure 7-1 were collected from a research vessel every 3 months (see caption to Figure 7-1).

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[17] Another sensor type was also deployed at Wilson B: the “miniDOT” (Precision Measurement Engineering). We have subsequently determined that the miniDOT sensors were unacceptably affected by biofouling that rendered that data invalid. See Appendix B.

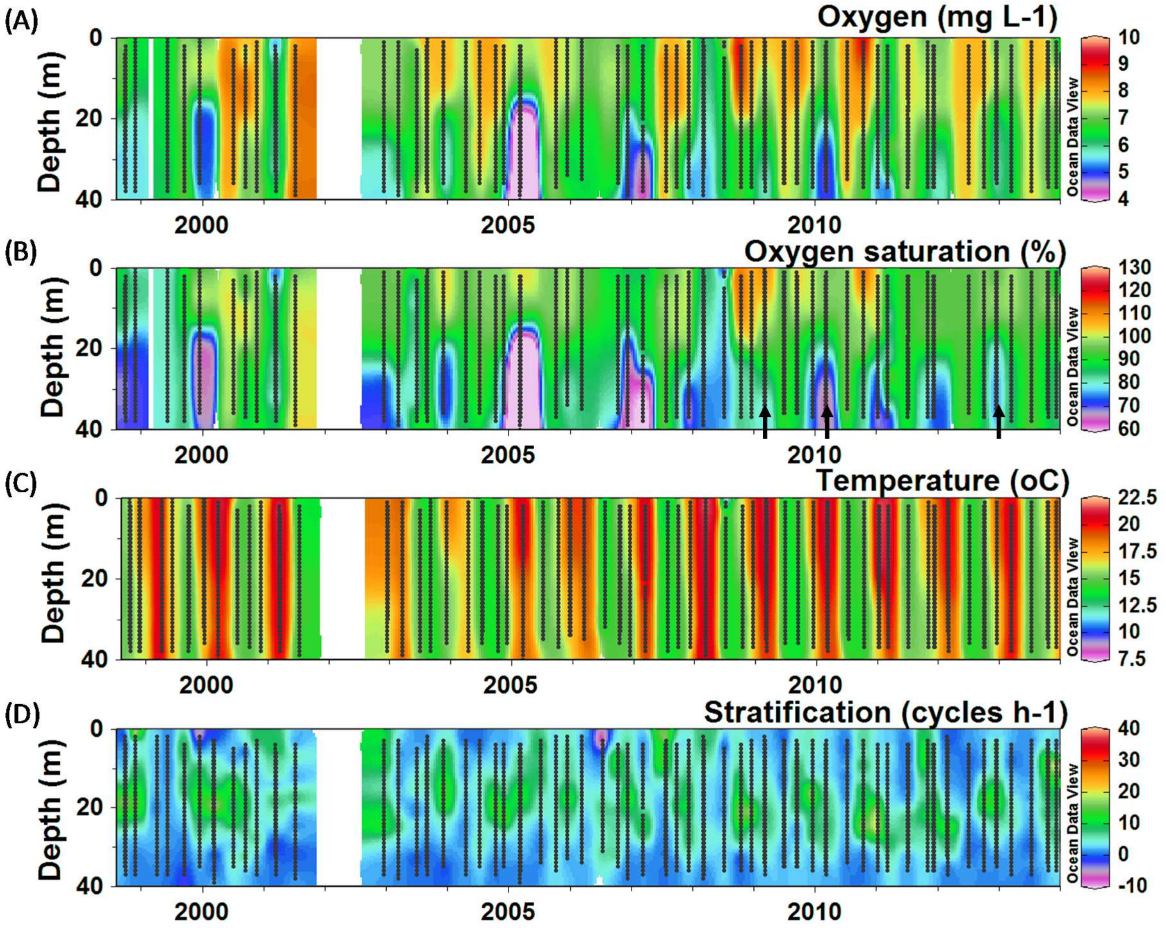

Figure 7-1: Temporal patterns in DO, temperature and water-column stratification at the extended-Firth monitoring site inferred from measurements made by sensors mounted on a CTD and lowered through the water column from a research vessel. The vessel visited the site every 3 months during the period 1998–2013. The black dots show the dates and vertical locations of DO records. The black arrows in panel (B) are referenced in Figure 7-2.

The data show:

- The upper 20 m of the water column at the extended-Firth monitoring site was generally well oxygenated (panels A and B), with greater than 90% DO saturation for much of the year.
- In summer and autumn (the higher temperatures in panel C), when the water column was stratified[18], DO typically reduced to about 60–70% saturation (4.9 and 5.7 mg L^{-1}, respectively) at levels in the water column greater than 20 m below the surface.

The data shown in Figure 7-1 were collected from a ship every 3 months. The moored instruments at the extended-Firth monitoring site and at Wilson B made measurements every 15 minutes, so they show more temporal detail.

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[18] Panel D shows the Brunt Väisälä frequency (*N*, units of cycles h^{-1}), which is indicative of water-column stratification: higher *N* means more strongly stratified.

The extended-Firth 15-minute data (2005–2014) (made with moored sensors) are quite consistent with the data shown in Figure 7-1. They show:

- In two of six years where the 15-minute record is complete, subsurface[19] DO remained below 60% saturation for several weeks (Figure 7-2). The lowest recorded subsurface DO was about 40% saturation (2.7 mg L^{-1}).
- On rare occasions, and for periods of only a few days, surface[20] DO dropped as low as 40% saturation (Figure 7-3). DO was low at the surface less often and for shorter periods (maximum of about two weeks) than it was in the subsurface.

Note that periods of lower DO nearly always occurred when the water column was stratified.

The Wilson B 15-minute data (January to April, 2013) show:

- At 5 m below the water surface, DO reached a minimum of 70–75 % saturation (Figure 7-4). At these times the water was colder and more saline, and subsurface DO at the extended-Firth monitoring site was also low (60% saturation).

Comparison of the extended-Firth 15-minute data with the Wilson B 15-minute data reveals an important detail:

- Less-than-saturation DO at Wilson B (5 m below the water surface) occurred just briefly (for between 40 and 60 minutes) on flooding tides and coincided with the appearance of colder and more saline water at the site. We interpret this as meaning that low-DO water that appears at Wilson B is the same low-DO bottom water that appears at the extended-Firth monitoring site, with currents transporting ("advecting") the water between the two sites.

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[19] "Subsurface" here means at 33 m below the surface.

[20] "Surface" here means at 10 m below the surface.

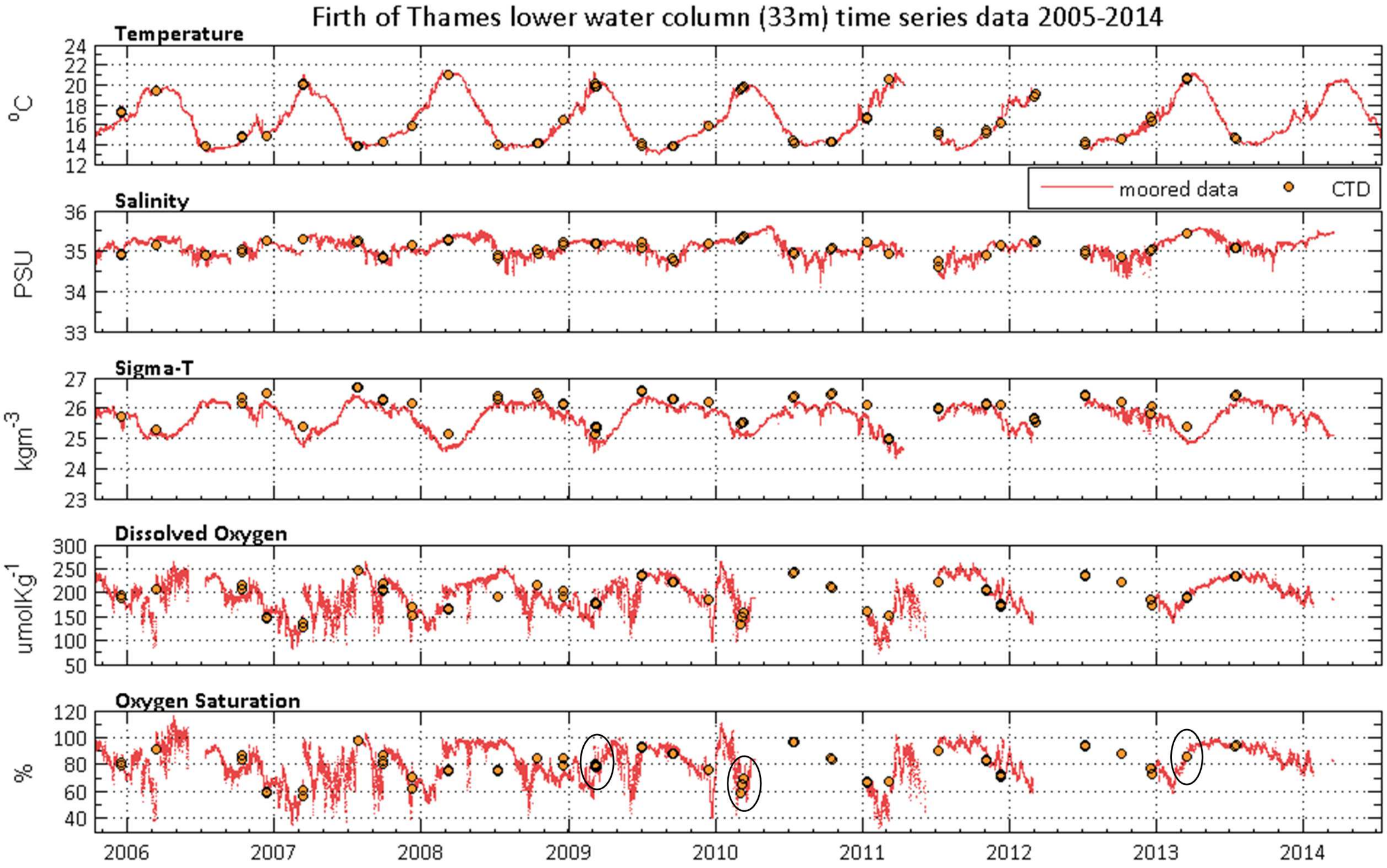

Figure 7-2: Time series from the extended-Firth monitoring site, 2005–2014. The data are from the lower water column, 33 m below the surface. The circled data in the % saturation plot are coincident with the CTD oxygen data arrowed in Figure 7-1. At a salinity of 35, 100 µmol O_2 kg^{-1} ≈ 3.3 mg O_2 L^{-1}.

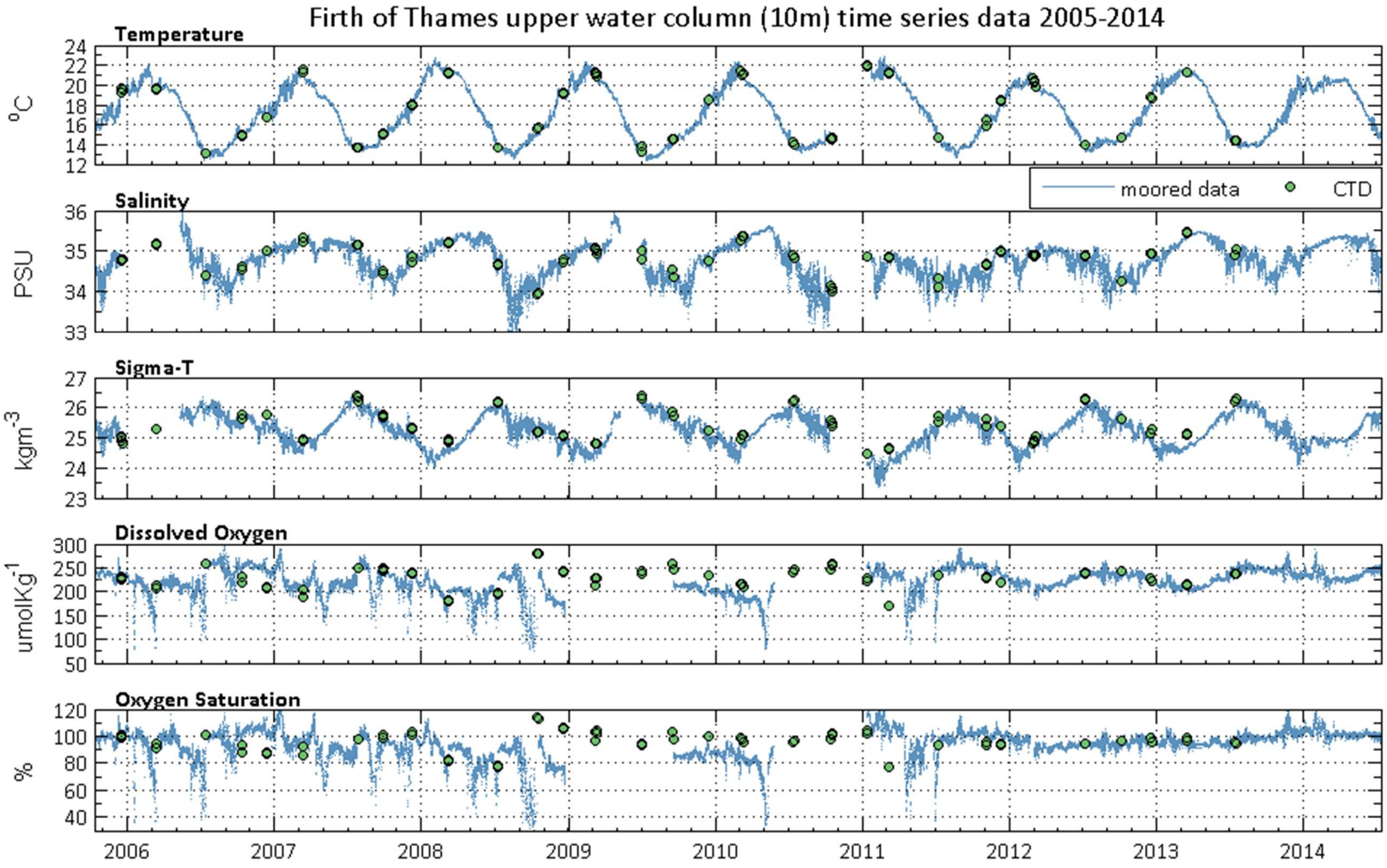

Figure 7-3: **Time series from the extended-Firth monitoring site, 2005–2014.** The data are from the upper water column, 10 m below the surface. At a salinity of 35, 100 µmol O_2 kg^{-1} ≈ 3.3 mg O_2 L^{-1}.

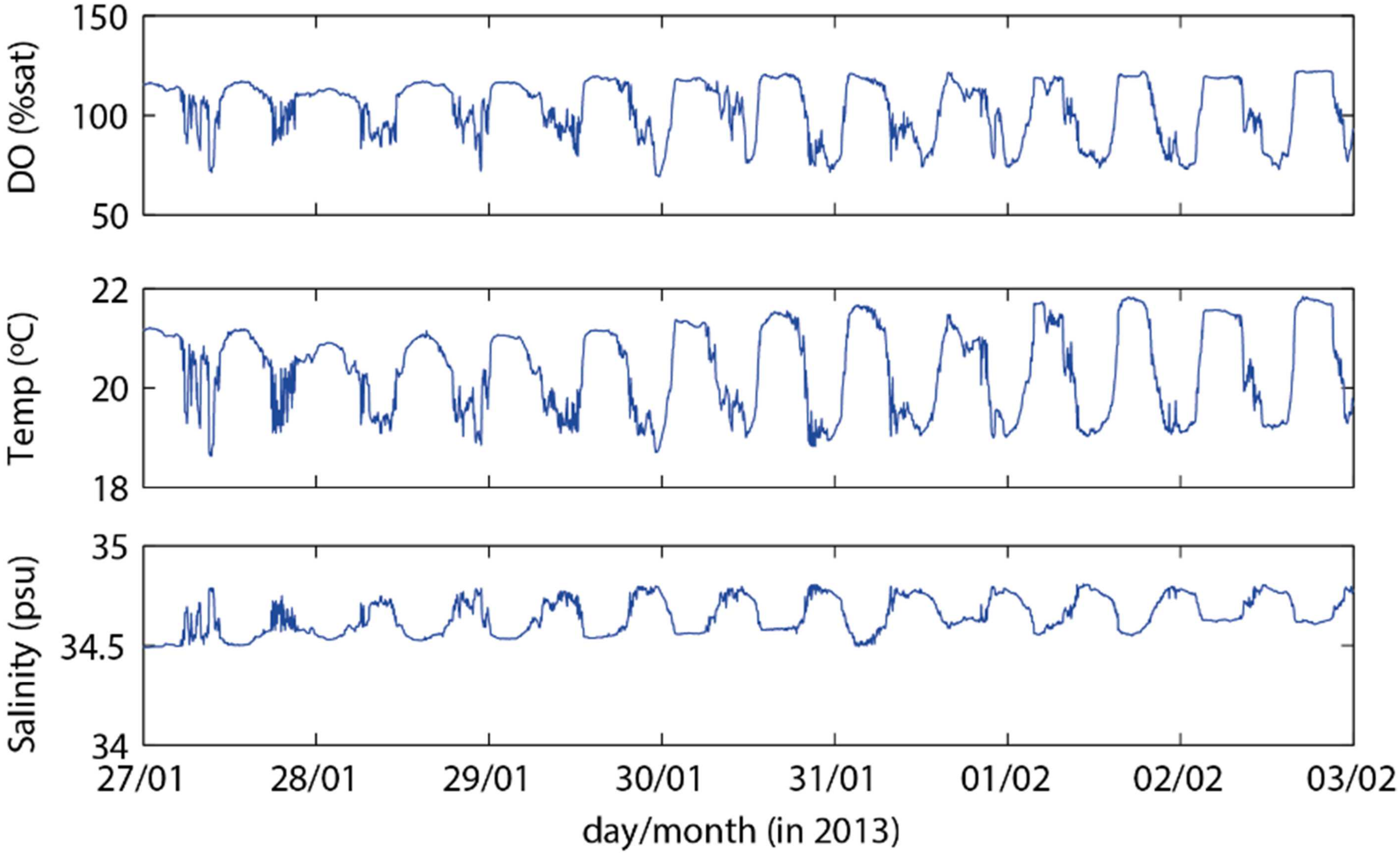

Figure 7-4: **DO, temperature and salinity at Wilson B (5 m below the water surface) from January 27 to February 3, 2013.**

Spatial surveys of DO conducted in autumn of each of three years show some further important features (Figure 7-5). For example, greatest oxygen depletion coincides with highest levels of phytoplankton deep in the water column (see, especially, the year 2010 in Figure 7-5). The extent of oxygen depletion is variable in strength from year to year[21]. Also, low DO, when it occurs, is contiguous between the extended-Firth monitoring site and Wilson B (not shown) but, moving into the Firth, the oxygen depletion becomes less pronounced. That is, the autumnal subsurface minimum is most intense in the extended Firth. A likely explanation is that the shallower water in the inner Firth inhibits water-column stratification, and this inhibition favours reoxygenation of the water column[22].

Figure 7-6, which shows oxygen data acquired in autumn in 3 separate years at 3 latitudes across the Gulf and Firth, provides more detail on the distribution of DO. For example, DO near the seabed reached 4.2 mg L^{-1} in the vicinity of Wilson Bay Areas A and B in autumn 2010. In autumn of 2009, DO near the seabed was 5.4 mg L^{-1}.

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[21] Some of that variability may arise because we sampled on slightly different days in different autumns.

[22] Stratification hinders reoxygenation from the atmosphere by capping mixing and overturn of the water column, hence the absence of stratification favours reoxygenation. Water-column stratification breaks down in shallow water because, amongst other things, bottom-generated turbulence associated with tidal currents, wind-generated currents and waves is more effective at mixing the water column.

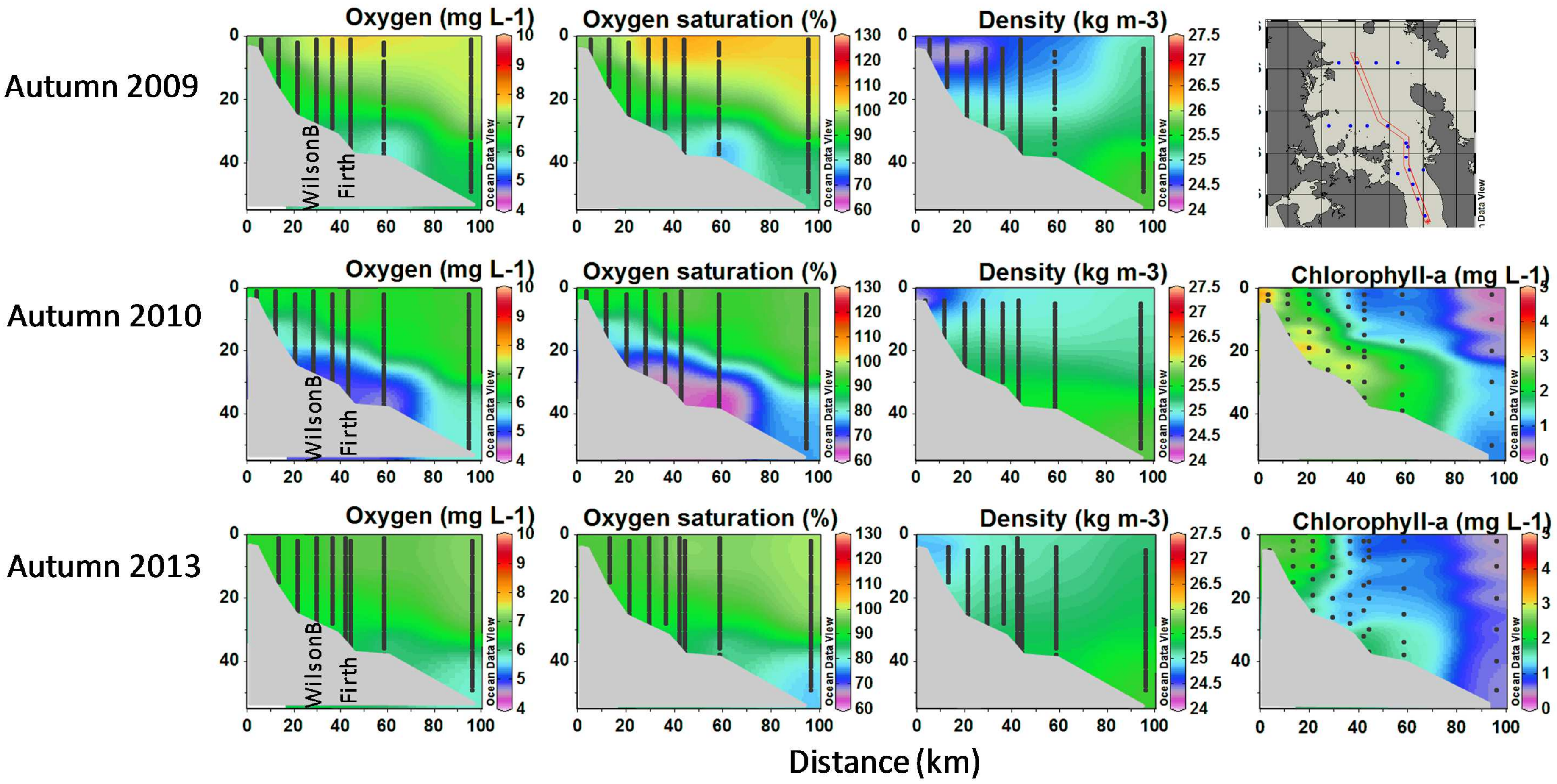

Figure 7-5: Autumn survey data, 2009, 2010 and 2013. Shown are oxygen concentration, oxygen saturation, seawater density and chlorophyll *a* at stations indicated in the inset map. The extended-Firth monitoring site and Wilson B mooring site are labelled in the left panels.

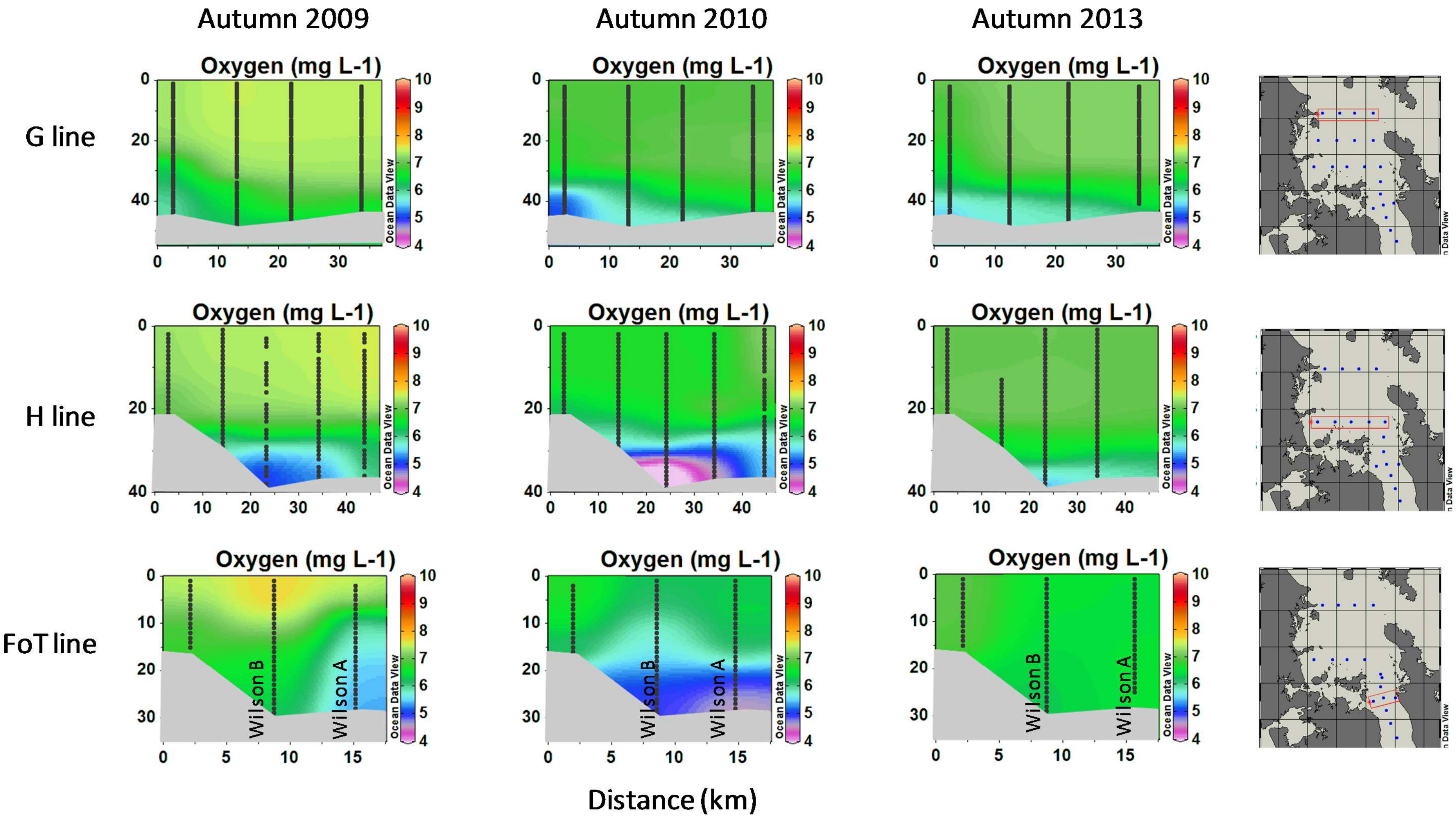

Figure 7-6: Oxygen in the Firth and Hauraki Gulf in autumn 2009, 2010 and 2013. Data are shown for 3 latitudinal sections.

7.3 Causes of oxygen depletion

We attribute the seasonal depletion of DO to a combination of at least two factors: strong stratification of the water column in late summer and autumn that inhibits oxygen exchange with the atmosphere which otherwise would replenish the DO in the water column; and consumption of oxygen by microbial respiration of sinking organic matter that has accrued from primary production in the immediately preceding spring and early summer.

The cold, high-salinity water that sometimes upwells from deep in the ocean onto the coastal shelf also tends to have low oxygen concentrations. **Nonetheless, we do not believe that this is the driver of the annual oxygen depletion that occurs in late summer/early autumn because upwelling is most frequent in late winter, spring and early summer.** Also, DO saturation in the upwelling water is rarely much below 80%. Thus, even if this water were to enter the extended Firth in the autumn, it could not, alone, be deemed to be the sole driver of the depressed oxygen.

7.4 Trends

We have conducted a trend analysis of the DO data shown in Figure 7-1. For this, we divided the DO data into two depth bins: the first bin was the top 20 m of the water column, and the second bin was everything below that, and we used the seasonal Kendall trend test for the analysis. **The result was that there was no trend in time in DO in either depth bin.** The results of the trend tests are tabulated in Appendix A.

Further analysis could examine relationships between water-column stratification and phytoplankton. The results might reveal more information on how stratification and organic matter influence oxygen depletion.

8 pH

8.1 Data

Carbonate system parameters (pH, partial pressure of CO_2 [pCO_2], dissolved inorganic carbon [DIC] and total alkalinity) were surveyed over the Firth and Hauraki Gulf during a voyage in autumn 2010 and during 4 seasonal voyages in 2012–13.

8.2 Results

The partial pressure of CO_2 was near or below atmospheric pressure in spring, reflecting spring-bloom consumption of CO_2 by actively growing phytoplankton. pCO_2 started to increase in summer and then peaked in autumn. Values were lowest in winter, being under-saturated with respect to the atmosphere over most of the region, when the water column was well mixed and phytoplankton were moderately abundant.

In summer and especially in autumn, there was a consistent decreasing seaward gradient in surface pCO_2, with maximal DIC oversaturation in the Firth of Thames, moderate oversaturation in the extended Firth of Thames, and values near neutral (atmospheric) in the Hauraki Gulf.

pH deep in the water column varies inter-annually. pH is near oceanic values (~8.05–8.1) in spring over the whole region, but starts dropping in summer. pH reaches its lowest value (~7.9) in autumn. pH increases in winter back toward oceanic values.

The pH minimum coincides with oxygen depletion. **From this, we can infer that the same combination of physical and metabolic processes that we believe to be driving DO is also driving the carbonate system.** That is, the same microbial respiration that consumes organic matter in the late summer and early autumn and produces CO_2 also pushes pH down to a minimum (most acidic) at the same time. Acidification lowers the calcium carbonate saturation state.

As further evidence of this connection we note that, at the extended-Firth monitoring site, higher pCO_2 and lower pH and saturation state occur near the seabed as opposed to near the sea surface (except in winter, when the water column is mixed). This indicates a metabolic association with oxygen consumption.

8.3 Trends

We have been observing carbonate system dynamics since 2009 but complete records started only with the 2010 survey. **This is too short a record to say anything about trends in the carbonate system.**

9 Mineralisation of organic matter

“Mineralisation” is the breakdown by living organisms of organic matter into inorganic substances. It is the opposite of the process of assimilation of inorganic nutrients into organic matter.

“Benthic” mineralisation occurs within and close to the seabed and “pelagic” mineralisation occurs in the water column.

Here we compare benthic and pelagic mineralisation, which have implications for the oxygen and carbonate system indicators of eutrophication (discussed in section 11.1 where we assess the trophic state of the Firth).

9.1 Benthic mineralisation

- The rate of benthic mineralisation of organic matter is highest in the inner Firth.
- At all sites that we have made measurements (which includes the Firth, the extended Firth and the inner Hauraki Gulf), there was net oxygen consumption by the sediments. That is, benthic respiration exceeded primary production at the seabed. Thus, the seabed was net heterotrophic. This was found to be the case regardless of water depth or bed-sediment type.

  Net heterotrophy means that more organic matter is mineralized than is synthesised. If the measurement period upon which this kind of conclusion is based is too short to accommodate natural cycles of production and destruction, then the “excess respiration” might be of stored organic matter generated within the system prior to the measurement period. However, in this case we believe that the necessary organic matter is fuelled by nutrients supplied from outside of the system, meaning from the ocean or supplied by rivers. We comment further on this in section 10.
- Net daily oxygen consumption by sediments was typically two times higher at sites in the inner Firth compared to sites in the extended Firth.
- Comparing measured fluxes of O_2 (and, by implication, CO_2) with corresponding flux and denitrification data from numerous Australian estuaries (reviewed in Eyre and Ferguson, 2002), we infer that denitrification efficiency (proportion of the nitrogen entering the seabed that is subsequently denitrified) may be maximum in the extended Firth and close to maximum in the inner Firth. Denitrification efficiency is dependent on the rate of input of organic matter to the bed sediments. **Hence, with efficiency already near or at maximum, further increases in organic matter to the seabed may reduce denitrification efficiency, depending on how close the system is to any threshold for decline in efficiency**.

  Denitrification measurements are required to assess if further increases in organic matter loadings to the seabed would have an effect on denitrification efficiency.

9.2 Pelagic mineralisation

- Measurements of pelagic oxygen demand in autumn showed strong net heterotrophy, with the rate of net O_2 drawdown (by respiration) at inner-Firth sites being about twice the rate at extended-Firth sites.

- Despite that, DO at inner-Firth sites remained high. We believe this is because the inner sites are in shallow water that does not stratify. Consequently, atmospheric oxygen is readily able to penetrate through the water column (see section 7). DO became depleted at extended-Firth sites, which were isolated from the atmosphere by water-column stratification.
- The ratio of water column-to-sediment respiration was 50:50 at inner-Firth sites and 90:10 at extended-Firth sites.

10 Water, salt and carbon/nutrient budgets

We developed a water budget, a salt budget and a carbon/nutrient budget for the Hauraki Gulf, extended Firth, and Firth of Thames. These help us to understand the relative importance of sources and the exchanges between different parts of the system.

We used the Land-Oceans Interaction in the Coastal Zone (LOICZ) biogeochemical budgeting procedure to produce the budgets. Each budget divides the region into 3 boxes (Figure 10-1).

The water and salt budgets are "conservative" meaning that water and salt do not change form. In contrast, the carbon/nutrient budget is non-conservative, reflecting the biogeochemical processes that transform these elements (e.g., assimilation of carbon into organic matter by autotrophs and the breakdown of organic matter into carbon dioxide by heterotrophs).

Net ecosystem metabolism (NEM) is the balance between primary production and decomposition of organic material by the system.

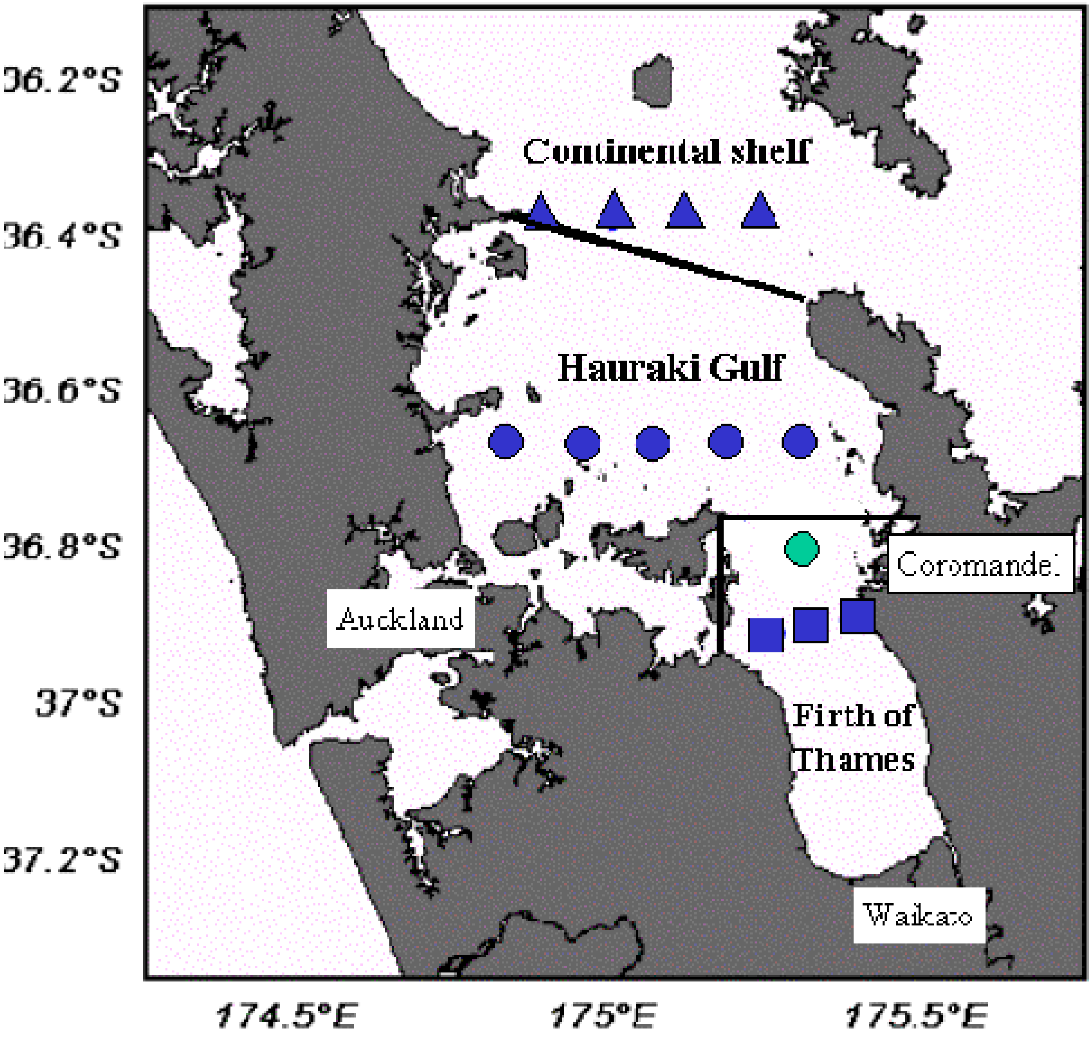

Figure 10-1: Division of the region into 3 boxes for the purpose of developing budgets. Note that the Firth of Thames as defined for the purposes of the budgeting includes what we are calling in this report the Firth of Thames plus the extended Firth (see Figure 1-1).

We used a wide range of data to construct the budgets. These include NIWA's numerous surveys of water quality in the Firth, the extended Firth and the Hauraki Gulf, estimates of freshwater nutrient loadings, river flow, rainfall, evaporation, and discharges of treated sewage effluent.

Because of data limitations, the budgets for the Gulf are valid for spring, summer and winter, while those for the Firth are valid for spring, summer and autumn. The budgets represent the conditions that prevailed during 2000–2001 surveys; at this time river flows were either close to average (for spring and autumn) or about 60% of average (for summer and winter). Sampling did not include conditions of strong upwelling.

Some key results are:

- Rivers that drain to the Firth contribute 57% of total N inputs (DIN + DON + PON) and 87% of DIN inputs to the Firth, with the remainder coming from offshore.
- The average time required to exchange the water volume of the Firth with the Gulf is 20 days. The exchange time of the Gulf with the shelf and the Firth is 32 days.
- The Firth appears to be a net importer of organic phosphorus and a net exporter of inorganic phosphorus. The phosphorus flux shows net decomposition of organic matter to inorganic nutrients and net production of dissolved inorganic carbon (e.g., CO_2). These observations are consistent with the view that the Firth waters are net heterotrophic (more organic matter is mineralized than is created on a net basis).
- The nitrogen balance is also non-conservative. In this case, the system is a net exporter of organic nitrogen and a net importer of inorganic nitrogen. Overall, much more nitrogen is imported than is exported. In contrast to phosphorus, nitrogen does have a gaseous phase. We infer that much of the "excess" nitrogen is not retained within the system. Rather, we believe that it is being denitrified and exported as N_2. The denitrification rates predicted from the budget are consistent with N_2 losses inferred from direct carbon and nutrient flux measurements made in shipboard experiments in the Firth. Further measurements are required to better constrain rates.
- For the Firth, the rate of primary production is, on average, slower than the rate of respiration of organic matter. This causes the net ecosystem metabolism to be heterotrophic. In contrast, the Hauraki Gulf is nearly balanced between autotrophy and heterotrophy.
- For the Firth, the excess of respiration over production (i.e., the net heterotrophy) must be subsidised by net import of substantial amounts of labile organic carbon from the land and/or from offshore.
- The Firth is a large denitrifier. About 73% of the total nitrogen export from the Firth (total = denitrification plus DON export) appears to be as N_2 gas. This helps to buffer the system against nitrogen loading from terrestrial and marine sources.
- On average, nitrogen in the Firth cycles about three times through the production–decomposition cycle before being lost to denitrification or (to a lesser extent) hydrographic export. This "amplifies" the effects of nitrogen imported to the Firth in terms of generating primary production.

11 Assessments of water quality and ecosystem health

11.1 The current trophic state of the system

Phytoplankton biomass and growth are known to be related to nutrient loading but the relationships between nutrient loading and the actual expression of the symptoms of eutrophication (including phytoplankton blooms and depletion of dissolved oxygen) are governed by physiographic “filters”. For instance, shallow estuaries with short water residence times flush phytoplankton to the sea before they can assume bloom proportions. Also, highly turbid systems limit light which in turn limits growth even under heavy nutrient loading.

The Firth and extended Firth are sensitive to nutrient enrichment (meaning that symptoms of eutrophication are not likely to be suppressed by physical factors such as turbid water/low light, short water residence time, and strong vertical mixing).

This makes the Firth more susceptible to adverse effects from sediment and/or nutrient inputs from the land than either shallower, more rapidly flushed estuaries or coastal waters along an energetic, open coastline.

Our reasons for this assessment are:

- the water is relatively clear[23], which means that light is available to drive primary production;
- the water residence time is long, which means the system is capable of supporting phytoplankton blooms that undergo complete life cycles of growth, retention and senescence;
- the water column is periodically stratified, which enhances the depletion of dissolved oxygen.

In this section, we look at the question of the trophic state of the system in a couple of different ways.

(a) It is not possible to evaluate trophic state simply by referring to nutrient concentrations in the water column. For one thing, physical factors such as light climate, water-column stratification, horizontal mixing and turbidity may all affect the expression of the actual symptoms of eutrophication[24]. Nevertheless, water-column nutrient concentrations have been used to assess “trophic state”, meaning, broadly, the extent to which the symptoms of eutrophication are expressed.

- ANZECC (2000) guideline trigger levels give a threshold of 30 mg DIN m^{-3} for “slightly disturbed estuarine water”[25], which is strictly relevant for southeast Australia only[26]. The water column-integrated median values of DIN at the extended-Firth monitoring site are typically less than this (about 20 mg m^{-3}, based on Figure 5-3).

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[23] Despite the high turbidity in the inner Firth in particular, enough light generally reaches the bottom to generate primary production.

[24] Including depleted DO, acidification and reducing conditions in bed sediments.

[25] To aid conversion among units note that 1 μmol L^{-1} DIN = 14 mg m^{-3} DIN.

[26] These guideline figures were derived using data from estuaries in SE Australia. There is an implicit assumption that, were data available from NZ estuaries, they would point toward a similar threshold being applicable.

- For southeastern USA estuaries Sheldon and Alber (2010) give limits of <25 mg DIN m^{-3}, 25–250 mg DIN m^{-3} and >250 mg DIN m^{-3} for water classified as “good”, “fair” and “poor”, respectively. The data in Figure 5-3 (roughly) place the waters at the extended-Firth monitoring site in the “good” category[27].

Further inshore, Vant (2011) measured nutrients and chlorophyll *a* in shallow subtidal Firth waters monthly at 3 sites during the period 2006–2007. Vant reported medians of 200–400 mg TN m^{-3} and 6–45 mg DIN m^{-3}. DIN varied over a very wide range of 6–940 mg m^{-3} with the high values (200–940 mg m^{-3}) occurring when phytoplankton growth became light-limited in winter. Vant’s median values place the waters of the inner Firth approximately in the “fair” category of Sheldon and Alber (2010).

(b) The NOAA Assessment of Estuarine Trophic Status (ASSETS) is a protocol for evaluating eutrophication based on the National Estuarine Eutrophication Assessment (NEEA) database (Bricker et al., 2003). ASSETS is an integrated method for eutrophication assessment that combines an index of overall pressure from human influence (OHI), an assessment of eutrophication status, and an index of the level of management of the system. The OHI uses a simple mass-balance model based on nutrient loading from the land and system susceptibility.

NOAA developed thresholds for chlorophyll *a* with a group of regional experts (Sutula, 2011) and concluded that estuaries with chlorophyll *a* during “annual bloom periods” less than 5 mg m^{-3} appear to show “low impacts”. Estuaries with annual-bloom chlorophyll *a* between 5 mg m^{-3} and 20 mg m^{-3} show “medium impacts” and estuaries with annual-bloom chlorophyll *a* in excess of 20 mg m^{-3} show “high impacts”. These thresholds refer to bloom conditions (Table 2 in Bricker et al., 2003) and should not be confused with annual means, which would be, by definition, considerably lower. “Impacts” include decline in submerged aquatic vegetation, shift in phytoplankton community structure, high turbidity and low bottom-water oxygen.

Within the European Union, the Water Framework Directive uses phytoplankton biomass, taxonomic composition, and abundance and frequency of plankton blooms as “biological quality” elements in a framework to categorize waterbodies by ecological condition (Sutula, 2011). The WFD uses chlorophyll *a* thresholds that are similar to those used by ASSETS: <5 mg m^{-3} is considered undisturbed or slightly disturbed, and >30 mg m^{-3} is highly disturbed or hypereutrophic.

Eleven years of data from moored fluorometers (Figure 11-1) at the extended-Firth monitoring site show that chlorophyll *a* in excess of 4 mg m^{-3} is often experienced in both the upper water column (7 m below the water surface) and the lower water column (20 m below the water surface). These are seasonal highs, occurring from late spring/early summer to autumn each year. The data also show that chlorophyll *a* at the extended-Firth monitoring site has exceeded 5 mg m^{-3} on rare occasions at both levels in the water column. The 5 mg m^{-3} threshold is approached and seasonally exceeded in the inner Firth, as shown by chlorophyll *a* maps produced from underway sampling during 2012–13 (Figure 11-2).

Vant (2011) summarised water-quality data from three sites in the southern Firth of Thames. The sites were sampled monthly for 13 months. Median chlorophyll *a* concentrations ranged from 2.3–4.0 mg m^{-3} (range 0.4–9.3). The 5 mg m^{-3} threshold had been exceeded on several sampling occasions in the southern Firth. Vant concluded that there were no obvious grounds for concern, however he

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[27] It is typically the case that little guidance is given on how threshold figures like these should be calculated/used. For instance, do they refer to depth-averages or the surface layer? Are they annual averages and, if so, what “type” of average (mean, median, maximum)?

did not have access to our extensive data from the extended Firth or to our 2012-13 underway sampling data, and based his conclusion upon his 13 months of southern Firth data alone.

To summarise, our data show that the Firth of Thames seasonally exceeds the NOAA ASSETS 5 mg m^{-3} chlorophyll *a* threshold for "medium impacts". This threshold is rarely exceeded at the extended-Firth monitoring site but it is frequently approached. Both regions are below the 20 mg m^{-3} "high impact" threshold. Thus, the ASSETS classification places the Firth in the "medium impacts" category while the extended Firth is at the upper end of "low impacts".

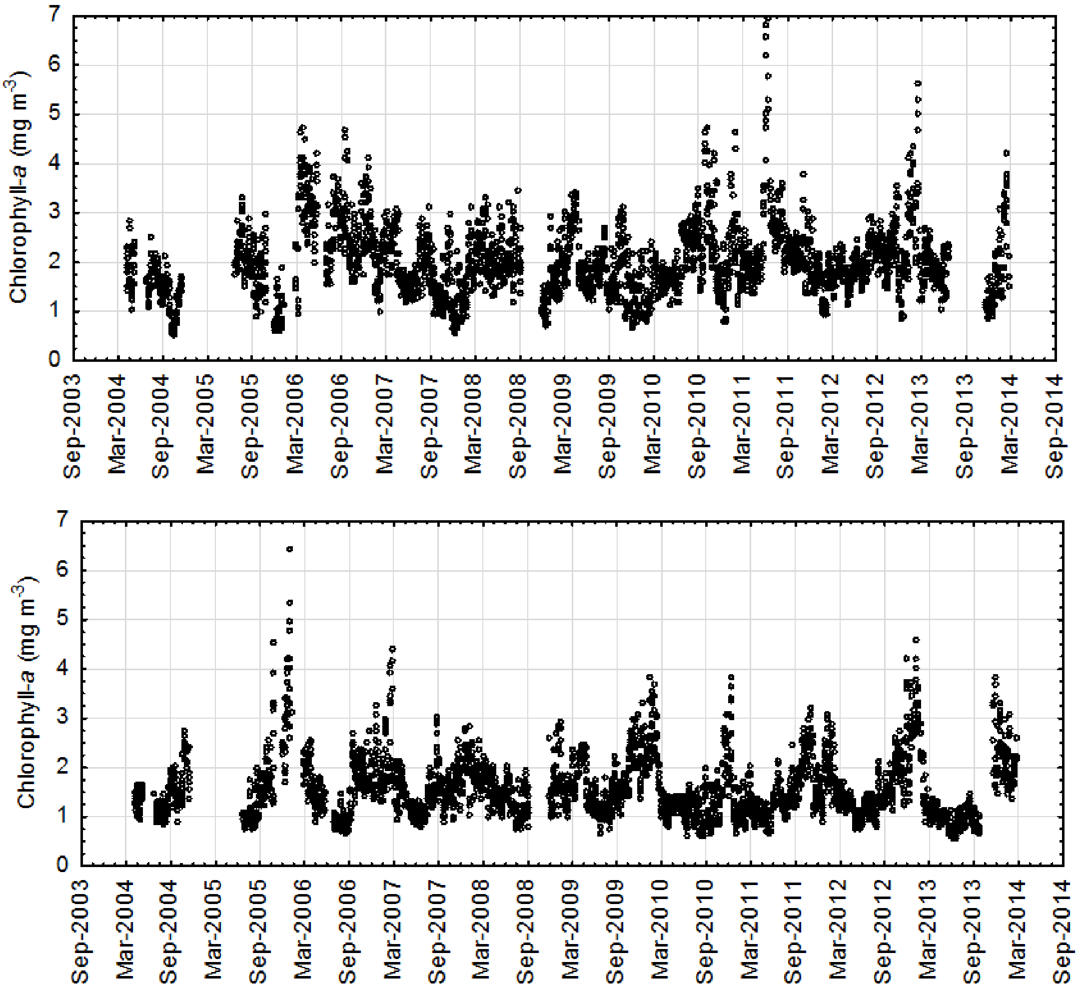

Figure 11-1: Time series of chlorophyll *a* measured by INF fluorometers at the extended-Firth monitoring site from 2004 to 2014. The upper panel shows data from the INF deployed 7 m below the water surface and the lower panel shows data from the INF at 20 m below the surface.

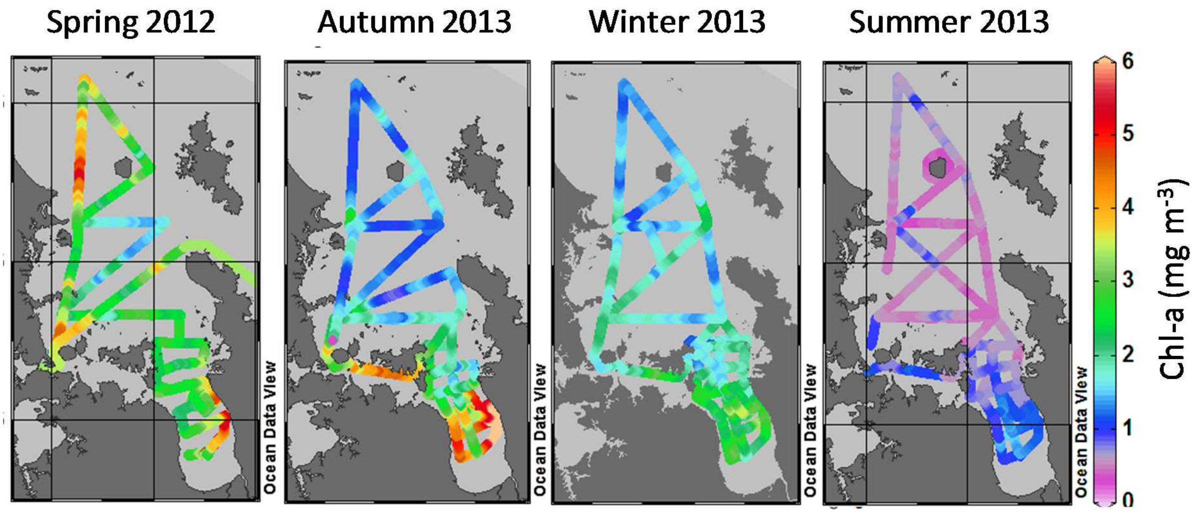

Figure 11-2: Surface chlorophyll *a* concentration mapped using underway sampling 2012–2013.

In a trophic rating system produced by Eyre and Ferguson (2009), sediments at outer and inner Firth sites are classified as “oligotrophic” and “approaching mesotrophic”, respectively. This is based on our experimental measurements of benthic mineralisation, described in section 9, from which denitrification efficiency was inferred. However, Eyre and Ferguson’s system applies strictly to Sydney metropolitan estuaries, and there appear to be issues in its application.

A commonly used trophic rating system for coastal waters based on water-column primary production rates (Nixon, 1995)[28], places the Firth and the extended Firth at the “mesotrophic” level of productivity. This is based on our experimental measurements of primary production averaged over all seasons from the inner Firth to the extended Firth (5 seasonal voyages) which found production to be about 191 g C m^{-2} y^{-1} (see Figure 6-2 for the voyage data). Systems with that level of productivity can be expected to export a high proportion (~45%) of production out of the upper water column to be degraded at depth by senescence and microbial processes.

Based primarily on our primary-production data, **we would describe the current state of the Firth and the extended Firth as mesotrophic**, where mesotrophic is the intermediate state between oligotrophic and eutrophic.

We comment below on what the pre-catchment-development trophic state of the Firth of Thames might have been.

11.2 The contribution of land runoff to nutrients

Our nutrient budget for the Firth (which is based on measurements collected during spring, summer and autumn during 2000–2001 only – see section 10) shows that the total nitrogen load to the Firth is dominated by land inputs (87% of DIN and 57% of TN)[29].

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[28] Nixon (1995) defined eutrophication as a process which increases the rate of supply of organic matter to an ecosystem. The Nixon (1995) trophic classification designates oligotrophic as <100, mesotrophic as 100–300, eutrophic as 301–500 and hypertrophic as >500 g C m^{-2} y^{-1} primary production.

[29] The budget does not apply to periods of strong ocean upwelling, which will bring more nutrients into the system, in which case the dominance of land inputs will be less. However, MacDiarmid et al. (2009) showed that upwelling-favourable conditions occur for only 11% of the time. MacDiarmid et al. (2009), OS2020 Bay of Islands Coastal Project: Phase 1 – Desktop study. NIWA Client Report WLG2009-3, 396 pp.

Cooper and Thomsen (1988), in comparing adjacent pasture, pine and native-forest clad catchments, found that leaching from pasture averaged about 3 times that from native-forested catchments. For the developed catchments of the Hauraki Plains, Vant (2011) estimated that point and diffuse human sources contribute 8% and 70% of the TN load to the major rivers, respectively, with "natural" sources making up the remainder.

Hence, we think it is likely that the balance between land-side and ocean-side nutrient loading was different prior to the historical land clearance and landuse intensification of the Hauraki Plains, specifically that **ocean-side loading was likely to have contributed a much larger percentage to a much lower overall nutrient load to the Firth**.

11.3 Trends

11.3.1 Cause(s) of the nitrogen trend at the extended-Firth monitoring site

We noted in section 5.2 that water-column-integrated DIN had increased at a rate of about 5% y^{-1} over the 15-year measurement period at the extended-Firth monitoring site. We looked at changes in an indicator of upwelling patterns and land-side nutrient runoff as possible explanations, but our analysis could find nothing that might fully explain the DIN trend. (We noted that the analysis of land-side nutrient runoff should be repeated with a focus on "terminal reach" river nutrient loads to provide a more nuanced view on whether there are trends in nutrient runoff that could match the trend we have found in water-column-integrated nitrogen, and river trends in DIN, in addition to trends in TN, need to be considered and understood. We also noted that further analyses need to be done on measurements of salinity and water temperature above and below the pycnocline, which could result from changed oceanographic conditions associated with changes to the upwelling regime.)

We mentioned that another possibility as a driver of the DIN trend is that there has been a change in the nitrogen dynamics of the system, which could result in a redistribution of nutrients across the various sediment, water and phytoplankton "compartments" that comprise the system. What we are talking about here is a possible change in denitrification efficiency, resulting in a decreased capacity of the system to vent nitrogen to the atmosphere. We briefly explore that possibility now.

- Studies in coastal systems have shown that denitrification efficiency drops with increased carbon loading (Eyre and Ferguson, 2002) and the attendant anoxia in bottom waters. This results in the system becoming less able to vent N_2 to the atmosphere, and a corresponding reduction in its resistance to eutrophication (Seitzinger, 1988). The mechanism by which this can occur was summarised by Sutula (2011) and described by Boynton and Kemp (2008). In essence, organic enrichment of sediments and low bottom-water oxygen result in sediment recycling of nitrogen becoming more "efficient", meaning that more of the organic nitrogen deposited to sediments is returned to the water column as ammonium (Kemp et al., 1990), which then is available to further fuel primary production. Given the importance of denitrification in the Firth (described in sections 9 and 10), this kind of shift in the seabed nitrogen dynamics could explain an increase in the water-column-integrated DIN.

  Further data and analysis are required to enable a more comprehensive assessment of the possible importance of this process.

We conclude that the cause of the trend in DIN at the extended-Firth monitoring site is likely to be complex, possibly including changes to oceanic inputs, terrestrial inputs, physical oceanography and/or denitrification efficiency.

11.3.2 Toxic and nuisance algae

The increases of large, predominately centric diatoms in the Firth has included increases in species known to be grazer-resistant. *Coscinodiscus wailesii* is one such example. This species has been recorded worldwide, developing blooms and damaging shellfish and macroalgal aquaculture and commercial fisheries[30] (Nagai et al., 1995; Nehring, 1998). Its distribution was first restricted to the tropical Pacific and West Atlantic oceans, but has spread to Europe, the USA and Japan in recent years (Rick and Dürselen, 1995; Nehring, 1998; Lange et al., 1992). In culture, *Coscinodiscus wailesii* has been shown to impede grazing by the copepods *Temora longicornis* and *Calanus helgolandicus* (Roy et al., 1989), which are genera with members that are commonly found in the Hauraki Gulf zooplankton community (Zeldis and Willis, 2014). We have not yet looked at whether *Coscinodiscus wailesii* in the Firth is approaching or has reached levels that are a concern.

Whilst toxic algae remain rare in the Firth, one genus (*Pseudo-nitzschia*) has become more abundant. Evidence linking changed nutrient loading and nutrient ratios with harmful algal blooms (HABs) is accumulating (Smayda, 1990; Smayda, 1997a and 1997b; Anderson et al., 2002; Glibert et al., 2005a; Glibert and Burkholder, 2006; Glibert et al., 2005b). In the Gulf of Mexico, the sedimentary record of *Pseudo-nitzschia* spp. shows increases in cell counts that parallel increased nitrate loading over the past several decades (Turner and Rabalais, 1991; Parsons et al., 2002). Although cell numbers of the toxin-producing diatom *Pseudo-nitzschia* have increased in the Firth, analysis of more than a decade of monitoring data from New Zealand waters by Rhodes et al. (2013) has not revealed any increase in frequency or magnitude of toxic events.

11.4 The pre-development trophic state of the system

In our opinion, **the Firth of Thames will at least have been "less mesotrophic" and may have been oligotrophic prior to catchment deforestation and subsequent development in the catchment**. We have no direct data to support our estimation of any previous trophic state of the Firth (that is, we do not have any actual measurements from the pre-historic period).

The reason for our opinion that the trophic state has shifted is simple: the total nitrogen load to the Firth is dominated by land-side inputs[31] and nutrient runoff from the land will have increased since catchment deforestation and subsequent development.

We are less sure what the shift in trophic state has been from. However, a very simple calculation suggests that primary productivity could have been about half what it is today. We arrive at that by simply reducing the land-side nitrogen loading by the amount we think is anthropogenic (about 75% according to Vant, 2011) and then multiplying that by the component of the marine DIN that we think is riverine (rivers supply about 87% of DIN to the total DIN load – see the nutrient budget in section 10), which gives a reduction in marine DIN of about 65%. Assuming the primary production is about proportional to the DIN loading (which we acknowledge is inexact), the primary productivity

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[30] The damage occurs through the likes of fouling of nets and clogging of filtration systems, not by any toxic effects.

[31] At least when there is no strong ocean upwelling; strong ocean upwelling occurs for about 10% of the time, as explained previously.

could be expected to reduce by about half. This would reduce the 2002–03 rate of 191 g C m^{-2} y^{-1} to about 100, which is the oligotrophic state of Nixon (1995).

11.5 Effects of low dissolved oxygen

11.5.1 Recent meta-analyses

There are recognised guidelines for dissolved oxygen to protect marine life, and organism responses to oxygen stress have been summarised in recent meta-analyses by Gray et al. (2002) and Vaquer-Sunyer and Duarte (2008) – see box, next page.

Referring to Figure 11-3 (panel A), fish and crustaceans had the highest lethal concentration thresholds, meaning that they were most susceptible to oxygen stress, followed by bivalves. Sublethal thresholds (where life-giving factors such as reduced growth and reproduction, increased physiologic stress, forced migration, reduction of suitable habitat, increased vulnerability to predation, and disruption of life-cycles were found to be highest) were greatest for fish and crustacea, followed by molluscs. Taxa with higher thresholds were generally also those with greatest potential mobility. Lethal times after exposure to acute hypoxia were shortest for crustacea and fish (order of few hours to a few days) while times for molluscs were a few hundred hours.

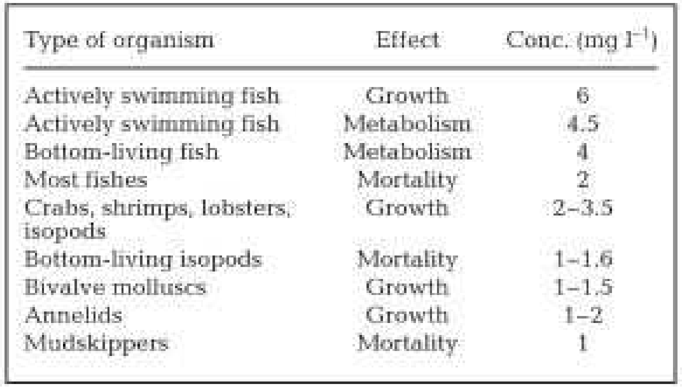
Vaquer-Sunyer and Duarte (2008) questioned the widespread use of the 2 mg DO L^{-1} threshold in conventional applications and recommended its upward revision. They showed that the 2 mg L^{-1} threshold is below the empirical sublethal and lethal thresholds for half the species they tested. They recommended 4.6 mg DO L^{-1} as "a precautionary limit to avoid catastrophic mortality events, except for the most sensitive (e.g., crab) species, and to effectively preserve biodiversity". Based on this information, Horizons Regional Council recommended 70% DO saturation in its One Plan for estuary management subzones.

Guidelines for dissolved oxygen to protect marine life include:

- Sheldon and Alber (2010) designated 3 mg DO L^{-1} as the "fair/poor" threshold and 5.5 mg DO L^{-1} as the "good/fair" threshold for Georgia (USA) estuaries.
- Batiuk et al. (2009) designated DO criteria for Chesapeake Bay for protection of individual ecological values (e.g., fisheries, habitat protection including larval recruitment, bivalve fisheries) in individual sub-regions of the Bay. Criteria include a 30-day mean of 5 mg DO L^{-1} applied to open-water habitats, with a 7-day mean of 4 mg DO L^{-1} and an instantaneous minimum of 3.2 mg DO L^{-1}.

Organism responses to oxygen stress have been summarised in recent meta-analyses by Gray et al. (2002) and Vaquer-Sunyer and Duarte (2008):

- Gray et al. (2002) outlined a taxonomic progression of decreasing sensitivities to DO stress, progressing from fish to crustaceans to annelids to bivalves. They tabulated their findings qualitatively for these groups in terms of DO concentrations that elicit various effects (Table 11-1).
- The findings of Vaquer-Sunyer and Duarte (2008) were largely in agreement with those of Gray et al. (2002) but were conducted within a formal statistical framework that used 872 experimental assessments across 206 marine benthic organisms. Figure 11-3 summarises their findings.



Type of organism	Effect	Conc. (mg l^{-1})
Actively swimming fish	Growth	6
Actively swimming fish	Metabolism	4.5
Bottom-living fish	Metabolism	4
Most fishes	Mortality	2
Crabs, shrimps, lobsters, isopods	Growth	2–3.5
Bottom-living isopods	Mortality	1–1.6
Bivalve molluscs	Growth	1–1.5
Annelids	Growth	1–2
Mudskippers	Mortality	1

Table 11-1: Results of Gray et al. (2002) for DO concentrations eliciting different effects in different taxonomic groups.

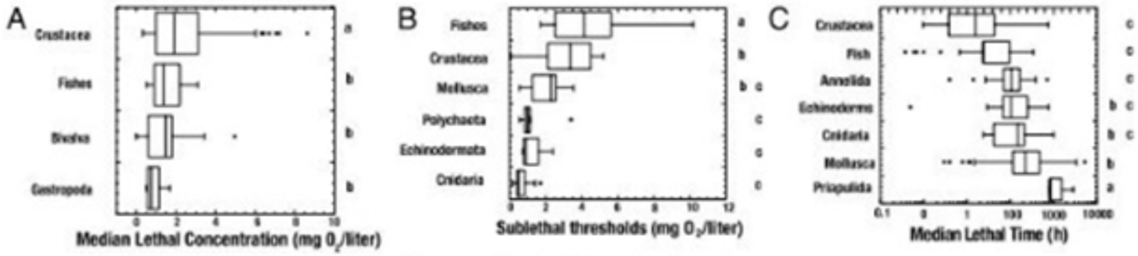


Figure 11-3: Box plot showing the distributions of oxygen thresholds among taxa. (A) Median lethal concentration (mg DO L^{-1}). (B) Median sublethal concentration (mg DO L^{-1}). (C) Median lethal time (h). The letters indicate the results of the Tukey HSD test, whereby the property examined did not differ significantly for taxa with the same letter. Adapted from Vaquer-Sunyer and Duarte (2008).

11.5.2 Green-lipped mussel farming

The meta-analyses indicate that bivalve molluscs are among the most resilient invertebrates to low oxygen, which is relevant to the observations of depleted DO in the vicinity of the Wilson Bay Marine Farm Zone.

Measurements made at Wilson B in 2013 (January 27 to February 3) showed DO at the surface dropping to 75% saturation, which is equivalent to 6 mg DO L^{-1} (Figure 7-4). The limited amount of data available suggest that the period sampled at Wilson B in Figure 7-4 was not an example of a particularly low autumn DO minimum. In autumn 2009 and autumn 2010 DO at the seabed dropped to 5.4 and 4.2 mg DO L^{-1} (Figure 7-6). Figure 7-2 also shows oxygen minima below 6 mg L^{-1} occurring in the lower water column at the extended-Firth monitoring site. Given that settled spat, rather than larvae, are used in farming operations, this may mean a reduced risk to operations arising from low DO in the farm area, although effects on farmed spat should be further investigated[32]. The vertical distribution of DO concentration should also be monitored.

Hence, oxygen conditions appear to be sufficient for green-lipped mussel farming in the Wilson Bay Marine Farm Zone. However, two factors need to be taken into account:

(1) We are unaware of information specific to oxygen tolerances of cultured *Perna canaliculus* adults. However, *P. canaliculus* are known to be resilient to low oxygen in intertidal habitats and are able to sustain themselves through long emersed periods (Marsden and Weatherhead, 1998), although this does incur a metabolic cost. The size of this cost has not been evaluated for immersed individuals experiencing low DO, and should be further investigated.

(2) Data do exist for *P. canaliculus* larvae and juveniles (spat) (Alfaro, 2005) which show significant and large negative effects on larval survival and settlement at 6 mg DO L^{-1}, with greatest negative effects occurring at low water flows (1 or 5 cm s^{-1}) in the experimental tanks. This oxygen level (6 mg DO L^{-1}) did not affect spat survival or settlement.

11.5.3 Fish farming

The most sensitive group to low oxygen in terms of sublethal effects is fish (Table 11-1, Figure 11-3), particularly active swimmers (Gray et al., 2002).

- This is relevant to fish farming in the Coromandel Fish Farm Zone, for which farming of yellowtail kingfish (*Seriola lalandi*) and hapuka (*Polyprion oxygeneios*) has been proposed. Bowyer et al. (2014) investigated interactive effects of water temperature (21, 24, 27°C) and DO (normoxic vs. hypoxic) on the growth rate, feed intake and digestive enzyme activity of yellowtail kingfish. The oxygen regimes used were highly variable ("hypoxic" conditions ranged from 3.3–5.3 mg DO L^{-1}) so it is difficult to draw firm conclusions from their results, but they did show a 13% decrease in specific growth rate under these oxygen conditions at 21°C. We know of no data for adult kingfish or hapuka performance.

Tolerances for farmed salmon can be discussed for comparison.

- As active swimmers, salmon have high oxygen requirements. The recommended minimum DO concentration is 6 mg L^{-1} (Sim-Smith and Forsythe, 2013) and concentrations below that

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[32] Furthermore, the extent to which low autumnal DO might influence farming operations will depend upon the timing of spat seeding and the duration of the presumed sensitive-age-span period.

are defined as hypoxic for salmon because they cause a decrease in blood oxygen, chronic stress and reduced growth. Even temporary fluctuations below 6 mg L^{-1} have been shown to adversely affect salmon performance in terms of appetite, stress responses and growth. These results indicate that the minimum DO concentration should be >70% saturation for optimal salmon growth, and should be >60 % saturation for the welfare of the fish.

We conclude that observations of oxygen minima below 6 mg L^{-1} in the lower water column at the extended-Firth monitoring site (with penetration into the upper water column on occasion – see section 7), when combined with the uncertain response of kingfish/hapuka to oxygen status, warrant further investigation vis-à-vis management of the Coromandel Fish Farm Zone, which is approximately 2 km ESE of the extended-Firth monitoring site.

11.5.4 Further comments

The biogeochemical environment itself is also subject to identifiable gradients of response to oxygen minima. For instance, there is a consistent decrease in denitrification efficiency (i.e., less N_2, and more NH_4, produced per unit nitrogen entering the seabed) as benthic DO decreases. In a review of the literature, Boynton and Kemp (2008) showed that more than 50% (up to about 80%) of the sedimented nitrogen is denitrified when bottom-water DO exceeds 6 mg L^{-1}, but only about 20% of the sedimented nitrogen is denitrified when bottom-water DO is in the range 3-5 mg L^{-1}. Bottom-water DO concentrations as low as 3–5 mg L^{-1} (approx. 90–150 μmol kg^{-1}) are not the norm in the Firth, but they have occurred intermittently (for periods of days to weeks) in most years at the extended Firth monitoring site (see Figure 7-2). Kemp et al. (2005) concluded that time scales of recovery from de-oxygenation range from weeks to months for denitrifying bacteria communities to years for macrofaunal bio-irrigators. Both are necessary for healthy denitrifying benthic systems.

11.6 Effects of acidification

Ocean acidification decreases the saturation state of calcium carbonate and solid carbonate structures as a result become less stable and prone to dissolution. Thus, acidification can have detrimental effects on species such as shellfish, kina and coralline algae that use carbonate for their solid structures, particularly in the juvenile life stages. pH has also been shown to have an influence upon the behaviour/physiology of non-calcareous organisms. Fish behaviour can be adversely affected and physiological effects have also been noted, especially for fish larvae. Some photosynthetic species, such as seagrasses, benefit from the increased presence of CO_2 and H_2CO_3 (rather than HCO_3^-) that accompanies falling pH. These changes, as well as directly affecting specific species, may also result in change in the ecosystem structure.

Work in New Zealand on local molluscan responses to acidification was recently reported at the "Future proofing New Zealand's shellfish aquaculture: Monitoring and adaptation to ocean acidification" workshop in Nelson (Capson and Guinotte, 2014). It was reported (N. Ragg, Cawthron Institute) that *P. canaliculus* larvae underwent significant (nearly 50%) reductions in growth rate in water with pH of 7.7 compared to water with pH of 8.0. Large effects on shell thickness were also demonstrated, though pH ranges were not detailed. V. Cummings (NIWA) reported responses for adult (5–14 months old) cockles, abalone, and flat oysters in terms of survival, respiration (abalone), growth, reburial (cockles), physical condition, weight loss, physiological condition and righting behaviour (abalone). The experimental scenarios tested were based on temperature predictions for oceanic New Zealand for 2050 and 2100 (range 11–21°C) and a decline of 0.3–0.4 pH units by 2100. It was found that, for each species, the scenarios tested affected almost all of the response variables assessed. Interactive effects of temperature and pH were noted for abalone and cockles. Negative influences on responses were observed even when aragonite saturation states were above 1, indicating cause for concern before environmental conditions reach under-saturation.

Management of the Firth needs to consider climate change effects and effects of resource use on pH. Continued monitoring is required to identify any trends in pH.

11.7 Reversibility and remediation

Since the total nitrogen load to the Firth is dominated by land-side nutrient inputs (at least when there is no strong ocean upwelling, which is the case for about 90% of the time) and nutrients fuel primary production, **we expect that a reduction in land-side nutrient inputs will reduce the organic-matter load of the Firth and the consequent oxygen depletion that occurs in the extended Firth towards the end of the phytoplankton growth season (late summer to early autumn)**.

However, **we cannot make any quantitative predictions of what changes might ensue following any specific reduction in land-side nutrients** until we have a more thorough understanding of the dynamics of the system. (This is the subject of ongoing and proposed research.)

Without a return to the former sediment macrobenthic community a full recovery to the pre-catchment-development pattern of nutrient cycling and water quality in the Firth seems unlikely.

12 Overview of NIWA data used in this report

12.1 Sediments

- GPS Monitoring of Rod Surface Elevation Table (RSET) benchmarks located along the Appletree Transect B since 2008.
- Aerial photographs of the southern Firth dating to the 1940s and early 1950s.
- Sediment cores collected from 12 sites collected in February 2005 along Appletree Transect B. Cores dated and analysed for bulk density and particle size.
- Sediment cores collected in February 2006 from the intertidal flats along a 1 km long, north–south transect aligned with the Appletree Transect B. Cores dated and X-rayed.
- Annual sediment budget estimated for the mangrove forest at the Appletree transect, a 1000 m transect seaward of the mangrove-forest fringe, and the lower intertidal and shallow subtidal.
- Voyage SEA0201, December 2002, occupying a total of 29 stations along transects in the Firth and extended Firth.
- Voyage KAH0310 in December 2003, occupying a reduced number of sites on the same transects.
- Voyage KAH1202 in March 2012, occupying one site (“outer”) in the extended Firth and two sites (“inner”) in the Firth.
- Voyage TAN9915 north of the Mokohinau Islands in a water depth of 125 m (site 5, 35° 48.83’S, 175° 1.83’E).

12.2 Nutrients

- 15 years (1998–2013) of measurements of nutrient concentrations across a suite of nutrients every 3 months at the extended-Firth monitoring site. Measurements by CTD containing a rosette sampler lowered from a research vessel. Samples typically from 6 levels in the water column.
- Surveys of nutrient concentrations across the Hauraki Gulf and Firth of Thames in spring, summer, autumn and winter of 2003 and also during 2012–13.
- Southern Oscillation Index (SOI) state and seasonal wind directions in the northeast North Island.
- Satellite remotely-sensed sea surface temperature (SST) data for the shelf north of the Gulf dating from 2003.

12.3 Phytoplankton and bacteria

- Phytoplankton pigment (chlorophyll *a* and phaeopigment) has been measured and microphytoplankton cells (>2 µm cell size) have been collected at the extended-Firth monitoring site seasonally (every 3 months) over the 15-year period 1998–2013. Water samples for analysis by CTD containing a rosette sampler lowered from a research vessel. Samples typically from 6 levels in the water column. Picophytoplankton (<2 µm cell size) and bacteria cells have been collected at the extended-Firth monitoring site since December 2002

- Chlorophyll *a* samples at CTD sites in the greater Hauraki Gulf and Firth that have been occupied at various times, dating from 1996. This includes chlorophyll *a* measurements from a grid pattern of stations from inner to outer Firth waters occupied in December (summer) 2002, March (autumn), July (winter), October (spring) and December (summer) 2003.

- Photosynthesis–irradiance determinations made onboard ship during primary-production experiments over 6 voyages from spring 1999 to summer 2000 at the extended-Firth monitoring site and at a site on the continental shelf.

- Data from two Integrating Natural Fluorometers (INFs) at the extended-Firth monitoring site. INFs positioned at 7 m and 20 m below the surface. Data were first collected in mid–2004, but most consistently after mid–2005.

- Chlorophyll *a* determined spatially using underway fluorometry during 4 seasonal voyages, 2012–13.
    - Spring – voyage KAH1209. Summer – voyage KAH1311. Autumn – voyage KAH1304. Winter – voyage KAH1306.

12.4 Dissolved oxygen

- 15 years (1998–2013) of measurements every 3 months at the extended-Firth monitoring site. Measurements by CTD lowered from a research vessel.

- Spatial surveys of DO conducted in autumn of each of three years.

- Measurements every 15 minutes at two depths in the water column on a fixed mooring at the extended-Firth monitoring site over the period 2005–2014.

- Measurements every 15 minutes at the Wilson B site at 5 m below the water surface over the period January to April, 2013

12.5 pH

- Voyage in autumn 2010 (KAH1002), comprising underway sampling and sampling with a CTD at stations. Variables sampled included carbonate parameters, oxygen, chlorophyll, dissolved organic matter, turbidity, temperature and salinity.

- 4 seasonal voyages in 2012–13, comprising underway sampling and sampling with a CTD at stations, collecting the same variables as in 2010.

  - Spring – voyage KAH1209. Summer – voyage KAH1311. Autumn – voyage KAH1304. Winter – voyage KAH1306.

12.6 Benthic and pelagic mineralisation

- Voyages KAH0310 in December 2003 and KAH1202 in March 2012 visiting subtidal sites around the Firth and extended Firth, examining nutrient and oxygen sediment fluxes and concentrations, sediment bulk properties and structure, porewater chemistry, benthic microalgae and infauna.
- Voyage TAN9915 from the inner Firth to the outer NE continental shelf examining sediment oxygen fluxes.
- NIWA biogeochemical study in the Firth in May 2012, inner and outer Firth sites examining sediment bulk properties and structure, porewater chemistry.

13 Recommendations for further research and data collection

13.1 Trends

- Trend analyses should be revisited using new methods that eschew the use of the *p* statistic to infer significance (McBride, G.B., Cole, R.G., Westbrooke, I., Jowett, I. (2013) Assessing environmentally significant effects: a better strength-of-evidence than a single *p* value? *Environmental Monitoring and Assessment*. 10.1007/s10661-013-3574-8).

13.2 Sediments

- Sediment loads in the Waihou and Piako Rivers need to be better measured to determine what fraction of the sediment burden in the Firth is related to present-day land sources.

- Further analysis of the Appletree dataset as part of an ongoing PhD research project (Andrew Swales, NIWA) is aimed at distinguishing between resuspension of sediments by waves and sediment delivered in river plumes to the southern Firth.

- The Appletree experiments, which are located in central southern Firth, could be repeated at sites along the eastern and western margins to quantify cross-Firth differences in the physical environment.

- In order to better understand the effects sediments are having on subtidal infaunal communities, community analyses using multivariate statistics could be undertaken on existing datasets, combining information from the bulk sediment and biogeochemical properties with the composition of the meiofaunal community. Meiofaunal indices for eutrophication and pollution could also be investigated (e.g., nematode to copepod ratios), as could information on environmental adaptations, which could be derived from more detailed speciation of the meiofaunal (and macrofaunal polychaete) samples.

- The Deltares sediment-transport model should be calibrated. The calibrated model should be used to simulate a wide and systematically-defined range of scenarios to confirm and quantify the tentative modelling results presented herein.

- An integrated freshwater–seawater monitoring network could be set up to collect baseline information and enable assessment of the effectiveness of any future catchment landuse change.

13.3 Nutrients

- Update nutrient budgets with new data collected in replicates during all seasons.

- More seasonally resolved data on pelagic and benthic nutrient metabolism are needed.

- Biogeochemical modelling of Gulf and Firth should be done to help develop our understanding of nutrient dynamics and enable predictions of system responses to nutrient loading.

- Direct or indirect measurements of denitrification efficiency would provide actual denitrification rates. Ongoing monitoring of denitrification would help determine seasonal and long-term changes to this likely important ecosystem service. Long-term (months) chamber experiments examining denitrification as function of organic matter loading, DO, bioturbation, etc.

- Terminal reach monitoring of nutrient loading from rivers would help quantify the land-derived loading to the Firth of Thames. Currently monitoring stations are located approximately 30 km upstream of Piako and Waihou River mouths, thus only providing indicative loads. Ongoing monitoring would provide better information on the degree of changes in loads.
- Analysis of existing datasets to elucidate drivers of nutrient dynamics.
- Measurements and ongoing monitoring in the Firth of Thames to fill information gaps.

13.4 Primary production

- Continued monitoring of the nutrient and phytoplankton trends at the extended-Firth monitoring site is needed to understand their past and potential future trajectories. This should be extended into the Firth.
- More seasonally resolved data on pelagic and benthic nutrient metabolism are needed.
- Datasets of HAB incidence collected at marine farms in the region could be assessed in the context of the results presented here.
- Other datasets available from NIWA but not analysed here include large data sets on micro- and mesozooplankton which could be assessed in the context of the results presented here.

13.5 Dissolved oxygen and pH

- Monitor DO and pH in the Firth of Thames
- Improve understanding of vertical distribution of oxygen concentration at the extended-Firth monitoring site and at Wilson Bay Area A and B and connectivity between these areas.
- Prioritise studies of low DO and carbonate state tolerances of adult and especially larval stages of Firth of Thames aquaculture species and larval/juvenile snapper and any key bentho-pelagic species.
- Continue monitoring and analysis of data from the extended-Firth monitoring site and associated spatially extensive surveys to enhance our present understanding of fundamental drivers of the Hauraki Gulf and Firth of Thames environment.
- Investigate whether remotely sensed data for total suspended solids, CDOM and chlorophyll *a* can provide a synoptic multi-year data set to compare with the oxygen and pH time series shown here.
- Look into the drivers of inter-annual variations in strength, duration and spatial extent of stratification.
- Biophysical modelling of oxygen and carbonate system dynamics could be used for scenario testing, e.g., of oceanic and catchment loading conditions.

14 Data catalogue

14.1 Sediments

- Dated sediment cores enable annual–decadal-scale patterns of sedimentation the intertidal flats and in the mangrove forests of the southern Firth to be reconstructed.
- Dated sediment cores collected by Bentley et al. (in prep) enable annual–decadal-scale patterns of sedimentation in the intertidal zone of the southern Firth to be reconstructed.
- Dated sediment cores collected by Nodder et al. (in prep) enable annual–decadal-scale patterns of sedimentation in the subtidal zones of the Firth and Hauraki Gulf to be reconstructed.
- Sediment surveys across the Firth and Gulf collected in NIWA research describe the distributions of bulk properties and biogeochemical character of Firth sediments.
- Remotely sensed data (MODIS / Aqua) describe time and space distributions of fine suspended material in the upper water column of the entire Hauraki region from 2003 to the present.
- Modelling of sediment dispersal by the Deltares modelling platform is available. The Deltares model is presently uncalibrated for sediments.

14.2 Nutrients

- Water, salt and nutrient mass-balance modelling and loading estimates.
- Sediment and water-column biogeochemistry, including oxygen, carbon and nutrient flux rates.
- Nutrient concentrations through the water column at the Firth of Thames monitoring site 1998–2014, measuring decadal-scale changes at seasonal frequencies across a suite of nutrients.
- Surveys of nutrient concentrations measured broadly across the Hauraki Gulf and Firth of Thames.

14.3 Primary production

- Ship surveys of phytoplankton biomass and production across the northeast continental shelf, Hauraki Gulf and the Firth of Thames, with high spatial resolution in the Firth.
- Phytoplankton and bacteria cell counts, biomass and community composition at the Firth of Thames monitoring site (1998–2014), showing decadal-scale changes at seasonal frequencies with high taxonomic resolution.
- Phytoplankton abundance measured by the biophysical mooring at the Firth monitoring site (2004–2014) at daily frequency and measured across the region using underway surveys (2012–13).
- Expert knowledge available to describe the status, changes and causes of change in phytoplankton and bacteria.

14.4 Dissolved oxygen and pH

- 13 years of oxygen profiling at the extended-Firth monitoring site, accompanied by a wide array of physical and biological co-variables.
- Numerous spatially extensive surveys over the region using CTD.
- 9 years of moored oxygen data with accompanying current, temperature, salinity and phytoplankton fluorescence data.
- 5 years of carbonate system dynamical information from ship-based underway and CTD sampling.
- Expert knowledge available to describe the status, changes and causes of change in the oxygen and carbonate systems.

15 Data assessment

15.1 Sediments

- Data cover all geomorphic regions of the Firth (from old mangrove forest to the subtidal Firth approaches). Numerous aspects of sedimentary structure and sediment accumulation rates are covered, in representative spatial distributions.
- More information on subtidal conditions, especially sediment accumulation rates in the inner Firth, is needed.
- Conditions preventing the recolonization of biogenic reefs in the subtidal environment warrant better understanding, including past biotic conditions and changes that limit current recruitment.
- More information is needed on likelihood of negative feedback effects on nutrient cycling from continued elevated rates of sedimentation, inputs of organic-carbon enriched sediment to the western Firth, and inputs of sediment enriched in total organic-matter to the eastern Firth.
- We have placed much reliance on interpretation of sediment cores that were collected along Appletree Transect B, which is located mid-way between the Waitakaruru and Piako Rivers. Transect B was selected for coring because sediments deposited here should preserve changes in physical conditions on the intertidal flats that are representative of the southern Firth in general, which is a relatively linear shoreline. Closer to the river mouths, sedimentation rates are likely to be more spatially variable, being influenced by strong gradients in sediment transport and deposition rates associated with hydrodynamic conditions characteristic of the more complex tidal-river channel, deltaic and levee environments.

15.2 Nutrients

- The sediment and pelagic chemistry findings describe mainly summer and autumn conditions and could be extended to other seasons.
- Further analysis of spatial and temporal aspects of nutrient distributions is possible using data collected over the last 12 years and in particular the last 3 years.
- New water, salt and nutrient mass-balance modelling is possible with existing data collected in the last 2 years.

15.3 Primary production

- The datasets described above are one-of-a-kind in New Zealand and very unusual overseas for their detail and breadth in time and space.
- Remote sensing of coastal-zone phytoplankton chlorophyll is still being developed for the Hauraki Gulf/Firth of Thames. This could greatly expand our views of phytoplankton dynamics of the region over weekly to decadal time scales and spatial scales of 100s of m to 100s of km.
- It would be advantageous to explore datasets of HAB incidence collected at marine farms in the region and to assess them in the context of the results presented herein.

- Other datasets available from this research but not analysed here include large datasets on micro- and mesozooplankton, which would be advantageous to assess in the context of the results presented herein.

15.4 Dissolved oxygen and pH

- Further investigation of the movement of low-oxygen waters should be undertaken.
- Better understanding of high-frequency variability in pH and saturation state is required, which is approachable with moored sensors (for pH) and ongoing carbonate system parameter sampling.
- Better understanding of sensitivity of local biota to low DO and acidification effects is needed, including aquaculture species (mussels, oysters, kingfish), wild fisheries species (especially larval snapper) and the key benthic burrow formers and bioturbators (planktonic and post-settlement life-cycle stages).
- Hydrodynamic and biogeochemical modelling should be applied to investigate oxygen and carbonate dynamics, including scenario testing of various oceanographic and landuse conditions. Various modelling platforms are available for this, some of which are already developed for this region.

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Appendix A Tabulation of results of trend tests

Table A-1: Non-parametric seasonal Kendall tests for time trends in water-column-integrated areal (m^{-2}) nutrient concentrations (µmol L^{-1}) and ratios. Data from the extended-Firth monitoring site, October 1998 to July 2013. Data are grouped by season (seasons used were: Sep – Nov, Dec – Feb, Mar – May, Jun – Aug for spring, summer, autumn and winter, respectively).

Nutrient variable	Sample size	Median value	*P*	Median slope (annual)	5 % confidence limit for slope	95 % confidence limit for slope	Percent annual change
DIN	57	43.3	0.01	2.22	0.78	3.26	5.14
NO_3- N	57	24.7	0.10	0.83	-0.1	1.91	3.37
NH_4 -N	57	18.6	0.03	0.85	0.11	1.45	4.55
DIP	57	14.6	0.69	-0.1	-0.31	0.17	-0.68
DIN/DIP	57	3.1	0.04	0.13	0.05	0.24	4.15
DRSi	47	408.0	0.25	-8.69	-18.23	3.49	-2.13
DON	53	278.7	0.02	4.92	1.49	8.31	1.76
DOP	51	6.9	0.04	-0.38	-0.7	-0.08	-5.48

Table A-2: Non-parametric seasonal Kendall tests for time trend in the Southern Oscillation Index. Data are from October 1998 to July 2013. Data are grouped by month.

Physical variable	Sample size	Median value	*P*	Median slope (annual)	5% confidence limit for slope	95% confidence limit for slope	Percent annual change
SOI	201	0.4	0.20	0.03	-0.01	0.06	7.14

Table A-3: Non-parametric seasonal Kendall tests for time trends in areal chlorophyll *a* and phaeopigment concentrations (mg m^{-2} x 10^{-3}). Data from the extended-Firth monitoring site, October 1998 to July 2013. Data are grouped by season (seasons used were: Sep – Nov, Dec – Feb, Mar – May, Jun – Aug for spring, summer, autumn and winter, respectively).

Chlorophyll variable	Sample size	Median value	*P*	Median Slope (annual)	5 % confidence limit for slope	95 % confidence limit for slope	Percent annual change
Chl-*a* >= 20 m	56	28.50	0.00	1.20	0.58	1.87	4.22
Chl-*a* < 20 m	56	24.08	0.51	-0.22	-1.02	0.46	-0.91
Phaeo >= 20 m	55	13.78	0.02	0.34	0.07	0.64	2.49
Phaeo < 20 m	55	12.79	0.11	-0.37	-0.73	0.02	-2.92

Table A-4 Non-parametric seasonal Kendall tests for time trends in cell counts (cells m^{-2} x 10^{-3}) integrated over the water column. Data from the extended-Firth monitoring site, October 1998 to July 2013. Data are grouped by season grouped by season (seasons used were: Sep – Nov, Dec – Feb, Mar – May, Jun – Aug for spring, summer, autumn and winter, respectively).

Counts	Sample size	Median value	*P*	Median slope (annual)	5 % C.L. for slope	95 % C.L. for slope	Percent annual change
All micro phyto	53	6938291	0.00	477211	223557	646149	6.9
Diatoms	53	1129149	0.03	51870	14361	96930	4.6
Dinoflagellates	53	237451	0.39	-5096	-18291	4258	-2.2
Others	53	5374044	0.00	361234	175643	477743	6.7
Large centric diatoms	53	341824	0.01	30252	8796	55277	8.9

Table A-5: Non-parametric seasonal Kendall tests for time trends in cell biomass (mg m^{-2} x 10^{-3}) integrated over the water column. Data from the extended-Firth monitoring site, October 1998 to July 2013. Data are grouped by season (seasons used were: Sep – Nov, Dec – Feb, Mar – May, Jun – Aug for spring, summer, autumn and winter, respectively).

Biomass	Sample size	Median value	*P*	Median slope (annual)	5 % C.L. for slope	95 % C.L. for slope	Percent annual change
All micro phyto	53	1050	0.07	26.33	0.98	42.67	2.51
Diatoms	53	358	0.36	9.4	-6.17	21.84	2.62
Dinoflagellates	53	301	0.33	-9.45	-25.17	4.74	-3.15
Others	53	232	0.01	13.94	6.98	21.43	6.02
Eukaryotic picos	42	724	0.65	10.64	-25.95	50.2	1.47
Prokaryotic picos	42	83	0.01	10.19	4.91	19.85	12.34
Bacteria	42	1287	0.01	90.53	35.77	140.11	7.03
Centric diatoms	53	207	0.07	8.8469	0.6135	21.8612	4.27

Table A-6: Non-parametric seasonal Kendall tests for time trends in toxic diatom cell counts (cells $m^{-2} \times 10^{-3}$) and biomass (mg $m^{-2} \times 10^{-3}$) integrated over the water column. Data from the extended-Firth monitoring site, October 1998 to July 2013. Data are grouped by season (seasons used were: Sep – Nov, Dec – Feb, Mar – May, Jun – Aug for spring, summer, autumn and winter, respectively).

Toxic Counts/Biomass	Sample size	Median value	*P*	Median slope (annual)	5 % C.L. for slope	95 % C.L. for slope	Percent annual change
Diatom counts	53	51012	0.00	5777	3126	10726	11.33
Diatom biomass	53	23.79	0.88	0.18	-2.18	1.42	0.75
Dinoflagellate counts	53	88289	0.06	-5868	-10661	-490	-6.65
Dinoflagellate biomass	53	52.4	0.30	-2.1	-4.94	0.88	-4.01

Table A-7: Non-parametric seasonal Kendall tests for time trends in oxygen concentrations (mg L^{-1}). Data from the extended-Firth monitoring site, October 1998 to July 2013. Data are grouped by season (seasons used were: Sep – Nov, Dec – Feb, Mar – May, Jun – Aug for spring, summer, autumn and winter, respectively).

Oxygen variable	Sample size	Median value	*P*	Median slope (annual)	5 % C.L. for slope	95 % C.L. for slope	Percent annual change
Oxygen <20 m depth	53	224.6	0.98	-0.05	-1.10	1.18	-0.03
Oxygen ≥ 20 m depth	53	198.2	0.66	0.21	-0.60	0.98	0.11

Appendix B Observations of depleted oxygen reported by O'Callaghan (2013)

Data from a miniDOT dissolved oxygen sensor deployed at Wilson B that were reported by O'Callaghan (2013) showed oxygen depletion in surface waters. This included the observation that during late winter through to spring 2012 surface waters in the Firth of Thames had dissolved oxygen levels of less than 4.1 mg L^{-1} over a period of 28 days.

We have subsequently determined that the miniDOT sensors were unacceptably affected by biofouling that rendered the data invalid.

As a result, we do not stand by the miniDOT data and observations based on that data presented in O'Callaghan (2013).

O'Callaghan, J. (2013) Dissolved oxygen variability in Hauraki Gulf. NIWA Client Report, WLG2013-42, 21 pp.