Verification of plankton depletion models against the Wilson Bay synoptic survey data

Feb 2005 ARC Technical Publication 256
Environment Waikato Technical Report No. 2005/08

Environment Waikato
REGIONAL COUNCIL

Auckland Regional Council
TE RAUHITANGA TAIAO

Verification of plankton depletion models against the Wilson Bay synoptic survey data

February 2005 ARC Technical Publication 256
Environment Waikato Technical Report No. 2005/08

Auckland Regional Council Technical Publication No. 256
Environment Waikato Technical Report No. 2005/08
ISBN 1-877353-71-X
ISSN 1175 205

www.arc.govt.nz

Printed on recycled paper

Verification of plankton depletion models against the Wilson Bay synoptic survey data

N Broekhuizen
J Oldman
K Image
M Gall
J Zeldis

Prepared for
Auckland Regional Council

NIWA Client Report: HAM2005-002
February 2005

NIWA Project: ARC04225

National Institute of Water & Atmospheric Research Ltd
Gate 10, Silverdale Road, Hamilton
P O Box 11115, Hamilton, New Zealand
Phone +64-7-856 7026, Fax +64-7-856 0151
www.niwa.co.nz

Contents

Reviewed by:

M. James

M James

Approved for release by:

Elliott

S Elliott

Formatting checked

A. Bartley

1 Executive Summary

Broekhuizen et al. (2004) present simulation results for the Firth of Thames that predict the possible consequences (for the planktonic component of the foodweb) associated with three different patterns of mussel aquaculture under several season/wind regimes. The three models that were used to make those simulations had not been verified against field data at the time that those 'scenario simulations' were made. Within this report we present the results of a verification exercise applied to two of the three models, and also to the hydrodynamic model which drives transport in the biological models. The first of the biological models is the 'biophysical model', the second is the 'logistic plankton model'. The verification exercise was conducted using biological models that were structurally and parametrically identical to those used for the scenario simulations of Broekhuizen et al. (2004).

The data that the models are verified against stem from a 'synoptic plankton survey' of the Wilson Bay area that was made by NIWA on behalf of Wilson Bay Group A mussel farming consortium in May 2003. Our analyses are based upon quantitative comparisons between simulation and observation, but in order to maintain the proprietary nature of the raw data we often restrict ourselves to presenting only summmaries and qualitative comparisons within this report.

Details of the synoptic survey are provided in a NIWA report to Group A (Gall, M.G. et al. 2003). A variety of data were collected; however impacts upon phytoplankton were estimated from samples made at 49 locations (defining a 7 x 7 grid) in and around Wilson Bay Area A. Gall et al. were required to assess whether the Area A farms (that had been developed by that time) were influencing the abundance and spatial distribution of phytoplankton. Clearly, it was impossible to make identical surveys (time & location) of the area with- and without the farms. Thus the magnitudes of any effects were inferred as follows. First, a surface was fitted through data stemming from all 49 locations within and around Area A. This was taken as providing a robust indication of the phytoplankton distribution and abundance in the presence of the Area A farms. They inferred what the distribution and abundance may have been in the absence of these farms by fitting a second surface – to the data stemming from those locations (somewhat) beyond the perimeter of Area A. Differences between the two surfaces were deemed to provide quantitative indications of the degree of farm-induced change. Henceforth, we will refer to this surface-fitting approach as the *surfaces method*. Gall et al. concluded that there was some evidence that the phytoplankton population was depleted throughout much of Area A and immediately to the north of Area A. Depletion was greatest immediately to the NE of Wilson Bay Area A. This was deemed to be consistent with the timing (relative to the tidal cycle) of the daily plankton mapping surveys and with the part of Area A that had been most extensively developed at that date.

For the purposes of this verification exercise, the hydrodynamic model and both biological models were run for the period 13 May – 30 May 2003. The last five days of this period span the period during which the data that are used for verification were collected. For each of the biological models a pair of simulations was made. In one member of the pair, farmed mussels were present ('with-farms simulation'); in the

other they were absent ('no-farms simulation'). The simulated results were sampled in the manner (locations and times) that was adopted during Gall et al.'s synoptic survey.

Stephens (2003) reports the details of the hydrodynamic simulations which, in turn, were used to drive the biological scenario simulations reported in Broekhuizen et al. (2004). The verification exercise described within this report revealed that, using the parameterisation adopted in Stephens (2003), the hydrodynamic model reproduces observed vertical temperature, salinity and velocity profiles during the May 2003 synoptic survey period adequately – albeit that there is a small tendency to underestimate the vertical gradients in these quantities (section 5). Further investigation indicated that this deficiency could be amended by reducing the upper limit to which the vertical diffusivity of momentum is allowed to climb (Appendix 1). To ensure that we were truly verifying (*cf* calibrating) the biological models used in Broekhuizen et al. (2004), we have driven them using the hydrodynamic forcing stemming from the original (*cf* recalibrated) parameterisation of the hydrodynamic model. The biophysical model has been revised since the simulations reported in Broekhuizen et al. (2004) were made. We present the verification results for the original version of the biophysical model in the main body of this report. In Appendix 2 we present the corresponding verification of the most recent version of the model.

In our discussions of the biological models, we will draw distinctions between: (a) local patterns (occurring within the farmed zone), near-field patterns (occurring within approx 5 km of Area A), and far field patterns (occurring beyond ~5 km from Area A). The synoptic survey data extend over an area which encompasses the local and near-field ranges, but do not extend much into the far-field.

The original version of the biophysical model successfully reproduces the transition from dinoflagellate-dominance in early/mid May 2003 to diatom dominance by the time of the synoptic survey. It reproduces the onshore/offshore decline in phytoplankton abundance in a qualitative sense, but exaggerates the magnitude of the decline, and yields a step-like abundance transition rather than the smooth transition evident in the field-data. The model reproduces the observed peak in phytoplankton abundance around the SE corner of the survey area – but again, in an exaggerated manner. Averaged across the 49 stations, simulated chlorophyll abundance was invariably below that inferred from the field data, but on each of the five sampling days the simulated sample average chlorophyll concentrations could not be distinguished from the field-data sample averages (t-test for comparison of sample means, $P>0.05$). The coefficient of variation in model-estimated station-specific chlorophyll abundance is more than double that for the field-data. Average simulated concentrations of dissolved inorganic nitrogen (DIN) invariably exceeded the corresponding field averages, but the differences were not significant on four of the five days (t-test for comparison of sample means, $P>0.05$).

The revised version of the biophysical model driven by the reparameterised hydrodynamic model predicts quantitatively similar trends – including the overly strong onshore/offshore abundance decline, but exhibits less 'random' (high-spatial frequency *cf* onshore/offshore trend) biomass variability.

To assess the simulated pattern of depletion, we compared the sampling results from the no-farms and with-farms simulations. If we restrict ourselves to considering only the (simulated) samples from the 5 days' x 49 sample stations, the model fails to reveal any depletion (indeed, mild enhancement is predicted). If we continue to restrict the comparison to the five days of the synoptic survey, but base it upon 5-day time-averaged results, depletion of upto ~10% is predicted around the NE of Area A Wilson Bay. Depletion at this location is in accord with that inferred from the field data, but the model also indicates an 'alternating band' of depletion and enrichment to the SW of Area A – for which there is no evidence in the field data. Averaged over the full 18 d period of the simulation, the biophysical model again indicates depletion of upto ~10% extending to the NE, and NW of Area A. The revised version of the biophysical model driven by the reparameterised hydrodynamic model performs better (Appendix 2) – in that predictions of change in around the SW of Area A are in better accord with the data (ie show little evidence of depletion or enhancement). To the NE and NW of Area A the predictions of the revised version of the biophysical model remain similar to those of the original – and consistent with the data.

We endeavoured to apply the surfaces method (that Gall et al. (2003) used to analyze the field data) to our simulation results, but found that the results were unreliable because of the excessively high 'intrinsic' (*ie* non-farm related) spatial variability predicted by the biophysical model.

Simulated chlorophyll concentrations yielded by the logistic model (driven by the original hydrodynamics) were below those measured – however this is to be expected. In this model, chlorophyll concentrations are tightly prescribed by the parameterisation. As required by the ARC, we did not modify the parameterisation of the model to better reflect the conditions that prevailed during the synoptic survey. Between-station variability in simulated chlorophyll concentrations was less than that in the biophysical model, but still exceeded that in the field data. Direct comparison of the no-farms and with-farms simulations indicated that, in the model, the farms were inducing little, or no depletion. Indeed, in some cases, enhancement was evident – though we believe this to be an artefact arising from 'sampling error'. As was the case with the biophysical model, the surfaces method was defeated the excessive predicted spatial variability in our simulated data.

In summary, if we estimate (simulated) farm-induced change by comparing the results of paired no-farms and with-farms simulations, the simulation models yield time-averaged estimates of depletion which are within the range (albeit at the lower end of this range) that was inferred from the surfaces method applied to the field-data; however the excessive fine-scale variability predicted by both models precludes a direct comparison of the results of the surfaces method applied to both the simulation results and the field data. Furthermore, the original version of the biophysical model generates some areas of depletion and enhancement to the SW of Area A which are not evident in the field data – or in the predictions stemming from the more recent version of the model (Appendix 2).

The purpose of this verification exercise was to determine how much credence to attach to the results of the scenario-simulations described in Broekhuizen et al. (2004). The simulations presented in Broekhuizen et al. (2004) indicate that, even if they become fully developed, the Wilson Bay farms will have only comparatively localised and subtle effects upon the plankton of the firth of Thames; however, they also indicate that larger impacts (both locally, and in the far-field) might be expected to be associated with a very large AMA (1000s of ha) in the western firth of Thames.

Our analysis suggests that, within the vicinity of Wilson Bay Area A, the models are neither dramatically over-predicting, nor dramatically under-predicting the degree of phytoplankton change induced by the Wilson Bay Area A farms. This lends some support to the nature and magnitude of near-field change predicted by the models under the alternative farming scenarios described in Broekhuizen et al. (2004). Nonetheless, we note that the verification has been restricted to a short period of time, and the immediate vicinity of Wilson Bay Area A. Whilst the models' satisfactory performance is encouraging, we cannot be certain that they perform equally well in the Wilson Bay area under differing hydrodynamic (currents, stratification) or environmental (irradiance, nutrient abundance) conditions. More importantly, since: (a) neither the hydrodynamic model nor the biological models have been verified against data from the putative Western Firth AMA considered by Broekhuizen et al. (2004), the predictions for that area of the Firth must be considered less robust than those made for the Wilson Bay area. This is especially true of the far-field changes predicted to be associated with the western Firth AMA (see below).

There are three reasons for our caution regarding far-field impacts – particularly in the western firth. Firstly, though the model and the field data from Wilson Bay both indicate that impacts in that region should be localised, the very absence of far-field impacts (in the field) has precluded any verification of the models' far-field predictions in situations where far-field impacts may occur (ie associated with a large western firth AMA). Secondly, neither the hydrodynamic model, nor the biological models have been verified against data from the western firth. Finally, as described in Appendix 2, the most recent version of the biophysical model appears to perform better than the original even in the immediate vicinity of Area A. Preliminary results stemming from the recent version indicate that the far-field predictions of the original and revised models do differ – both in the near-field around Wilson Bay (Appendix 2), and in the far field around a putative Western Firth AMA (not shown). With the revised model the time-averaged local-scale and near-field depletion around the putative western Firth AMA are similar to those predicted by the original model, but the 'halos' of far-field change tend to be spatially smoother and show fewer 'signals' of far-field change arising 'out of nowhere' (*ie* without a clear precursor closer to the farm).

2 Introduction

The Auckland Regional Council is examining the possibility of implementing an aquaculture management area (AMA) in the western Firth of Thames. As part of this exercise, they are seeking to establish the likely ecological impacts of such an AMA. To this end, the Auckland Regional Council and Environment Waikato commissioned a review of the relevant field data for the area (Broekhuizen, N. et al. 2002). Together with the Western Firth Mussel Consortium, they then went on to commission a simulation study aimed at identifying the magnitude and spatial extent of any depletion (or enhancement) of the plankton community due to the presence of an AMA (Broekhuizen, N. et al. 2004). The biological models used in the latter study stemmed from Foundation for Research in Science & Technology funded research. The models continue to be evolve with Foundation funding. At the time of the study by Broekhuizen et al. (2004), they had not been formally verified against field data.

In the May 2003 NIWA made an intensive five-day study of the plankton abundance within and around the mussel farms located within Area A, Wilson Bay (on the eastern side of the Firth of Thames). This survey (henceforth, referred to as the 'synoptic survey') was commissioned by the Wilson Bay Group A in support of their application to develop further farm blocks within Area A. The resultant data stem from what is, at present, New Zealand's largest mussel farm (by area). They provide a means by which the models described in the preceding paragraph might be verified.

Auckland Regional Council together with Environment Waikato commissioned NIWA to undertake the aforementioned verification – the subject of this report. Group A granted permission for NIWA to make use of their synoptic survey data for the purpose of verifying the model. In order to protect the confidentiality of the synoptic survey data we restrict ourselves to presenting only qualitative indications of the field-data in this report – however the underlying comparisons were quantitative. In order to ensure that the verification results can be used to ascertain the degree of likelihood that should be attached to the results presented in Broekhuizen et al. (2004), NIWA were instructed that the verification exercise should use models that were not only structurally identical (*ie* retaining the same process formulations), but also parametrically identical to those used in the earlier simulations.

After providing some further details regarding methodological details and the environmental conditions that prevailed during the period of the synoptic survey we will present verification results (for the 'original' versions of the hydrodynamic and biological models) in the following order: (a) hydrodynamic, (b) biophysical, and (c) logistic plankton. We conclude the main body of the report with a section discussing implications for the interpretation of the results presented in Broekhuizen et al. (2004). In Appendix 1, we summarise results stemming from a recalibrated version of the hydrodynamic model. In Appendix 2, we present verification results from the latest version of the biophysical model.

2.1 Nature of the verification exercise for the biological models

In this verification exercise we seek to determine whether:

1. The biophysical model can successfully reproduce the trends in abundance of the limiting nutrient (dissolved inorganic nutrient), diatoms, phytoflagellates and dinoflagellates in the vicinity of Wilson Bay over the weeks leading up to and including the synoptic survey.
2. The biophysical and logistic models can reproduce the biomasses and magnitude of farm-induced change inferred from the synoptic survey by Gall et al. (2003) at:
    a. the 'bay-scale' (*ie* averaged across all 49 stations);
    b. a finer scale (*ie* on a station-by-station basis).

The synoptic survey data span a period of only five days. In order to address (1), we augment the synoptic survey data with additional Group A-owned data stemming from samples taken at five locations in and around Area A approximately two weeks before the synoptic survey. This enables us to derive field estimates of the abundance trends of the diatoms, dinoflagelaltes and 'other phytoplankton' in the field – against which the biophysical model's predictions can be compared. We address (2) by two means: (a) comparison of the inferences drawn from the differences between with-farms and no-farms simulation results and those drawn from the surfaces method applied to the field-data, and (b) application of the surfaces method to the results of the with-farm simulations and comparison of these results with those derived from the field-data. In our discussions of the biological models, we will draw distinctions between: (a) local patterns (occurring within the farmed zone), near-field patterns (occurring within approx 5 km of Area A), and far field patterns (occurring beyond ~5 km from Area A). The synoptic survey data extend over an area which encompasses the local and near-field ranges, but do not extend much into the far-field.

2.2 The Biological Models

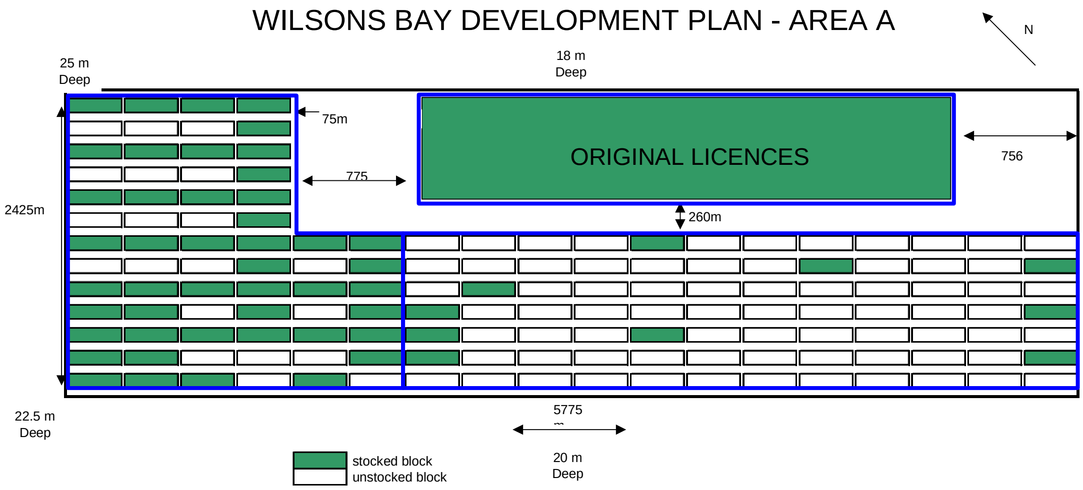
Broekhuizen et al. (2004) used two different biological models. Both are spatially explicit (750 x 750 m horizontal resolution and 2 m vertical resolution near the sea-surface). Both are driven by time-series of currents, temperature and salinity generated by running the Danish Hydraulic Institute's 3-dimensional hydrodynamic model (see section 3.0). One (the 'biophysical model') is a physiologically based model aiming to represent the dynamics of three groups of phytoplankton (diatoms, phytoflagellates and dinoflagellates), two nutrients (dissolved inorganic nitrogen, dissolved reactive silicon) and particulate organic detritus. The second (the 'empirical model') is much simpler in the sense that it lacks a sophisticated physiological representation, but it aims to represent a greater diversity of plankton – ranging from fast-growing, but vulnerable (to mussel predation) phytoplankton, through to slow-growing (but less vulnerable) zooplankton, and on to fish eggs and larvae. This second model can be sub-divided into two components: the fish egg/larvae model, and the plankton model. The synoptic survey data against which we are verifying the models do not provide information on fish larvae. Thus, that part of the empirical model is not considered further within this report. In the empirical model, the dynamics of the 'true plankton' are based upon the logistic growth equation. For this reason, and because we are not considering fish eggs/larvae further within this report, we will often refer to the empirical model as the logistic model. Further details of the models can be found in Broekhuizen et al. (2004).

2.3 The Wilson Bay Farming operations

Environment Waikato (henceforth, EW) have identified two sub-areas within the Wilson Bay area as having the potential to be developed for marine aquaculture. These are referred to as Areas A & B. To date, farming operations have been restricted to Area A – the more inshore of the two areas. Within Area A, there are three distinct areas of farm development (Individual farm-blocks (small rectangles in Figure 1) are 250 m x 110 m, and separated by 75 m. The properties of the farms within each sub-area (length of dropper ha^{-1} of farm, mussel size-class composition and density m^{-1} of dropper, dropper depth etc.) were collated from information supplied by the various operators within Area A when the original synoptic survey data were analysed.

Figure 1

Illustration of the arrangement of individual farm blocks within Wilson Bay, Area A during May 2003. The sub-area 'original licenses' is occupied by farms that were in place prior to 2001. The remaining blocks are licensed to members of the Group A consortium. Shaded farm-blocks are those stocked at the time of the survey. For the purposes of modelling, we divided Area A into three sub-areas (blue polygons) corresponding to: (a) the original licenses area; (b) a 'high density Group A area' (L-shaped polygon) and (c) a 'low density Group A area' (sparsely filled blue rectangle).



2.4 Synoptic Survey

In 2003, Group A mussel farming consortium commissioned NIWA to conduct a synoptic survey of plankton depletion within and around Area A. This survey was made over the period 24th - 29th May 2003. Details of the methods and results are presented in a NIWA client report to Group A (Gall, M.G. et al. 2003). The plankton sampling program involved the repeated sampling of plankton abundance at 49 stations distributed in and around the farm. Each round of sampling took place over a 3-4 hour period, with successive rounds occurring around the time of alternate low-tides. Sampling was depth integrated (sea-surface to approx. 10 m depth). Due to gear-failures, the survey was not completed on the fifth day and there are insufficient data to permit robust surfaces to be derived. The water-samples were filtered and total chlorophyll abundance measured. Samples were also preserved for possible future analysis of the taxonomic composition of the phytoplankton and zooplankton. A sub-set of these samples (25 station's worth on each of the first and last day of the synoptic survey) were analysed as a part of the work conducted within this verification contract. During the periods between the station-sampling, the research vessel towed an instrument along fixed transects to measure water-column properties including temperature, salinity (which provide indications of how well mixed the water-mass is) and in-situ fluorescence (which provides an index of phytoplankton abundance).

Gall et al. estimated the extent to which the Area A farms may have been modifying the local plankton abundance as follows (henceforth, we will refer to this as the *surfaces method*). For the first four days of the synoptic survey, Gall et al. (2003) fitted bivariate, cubic polynomials through (subsets of) the chlorophyll abundance data from the 49-station survey. The first surface (henceforth, referred to as S_{all}) was fitted to all 49 stations-worth of data. A second surface (S_{out}) was fitted, but in this case stations located within- and to the immediate north of Area A were excluded (Figure 2 & 3). This was based upon an explicit assumption that the excluded stations may have been strongly influenced by the presence of the farm, whilst those that were retained would are likely to have been less influenced. A third surface (S_{perim}) was fitted to the chlorophyll data stemming from the perimeter stations of the survey grid (Figure 2 & 3). Two estimates of location-specific relative chlorophyll change were made. The first was calculated as: $\frac{S_{all}(i,j) - S_{out}(i,j)}{S_{out}(i,j)}$. The second was calculated as: $\frac{S_{all}(i,j) - S_{perim}(i,j)}{S_{perim}(i,j)}$ (where the (i,j) notation is used to indicate that corresponding, location-specific values were extracted from each surface). We will refer to these latter two surfaces as 'change surfaces'. In addition to the four, daily surface-triples, they also derived a four-day average triple. Rather than deriving these time-averaged surfaces from the four-day averaged biomass at each of the 49 stations, the four-day average change surface was derived from the difference between the four-day averaged values of S_{all} and S_{out} (S_{perim}).

The method assumes that any differences between the shapes of the two surfaces used in a comparison can be attributed solely to the influence of the farms. The assumptions behind this method are: (a) that farm effects would be most dramatic within the farm, and negligible around the perimeter of the sampling grid; (b) that those parts of the surfaces S_{perim} (or S_{out}), which lie within Area A's perimeter provide reasonable approximations of the chlorophyll concentrations that would have held within Area A (and its immediate vicinity) had there been no farms present; (c) that the surface S_{all} provides a good indication of the realised chlorophyll field – which reflects both 'intrinsic' spatial variability and potential modifications to this associated with the presence of the farms within Area A. Averaging over the synoptic-survey period, the surfaces method implied that maximum local depletion occurred around the NE corner of Area A. Lesser depletion was evident throughout Area A, and extended somewhat to the north of Area A. Averaged over the entire area of the survey grid, the surfaces-method implied that chlorophyll abundance was reduced by less than 10% relative to what may have been expected in the absence of the farm.

Figure 2

Illustration of the Firth of Thames showing depth contours, the locations of the 49 stations that were repeatedly occupied during the synoptic survey, and also indicating the horizontal resolution of the model grids (adjacent tick-marks are 375 m apart; model grid-cells were 750 m x 750 m horizontally). Note that, given the model's horizontal resolution and the bathymetric data used to define the sea-floor, several of the inshore most stations appear to have been on dry-land within the models.

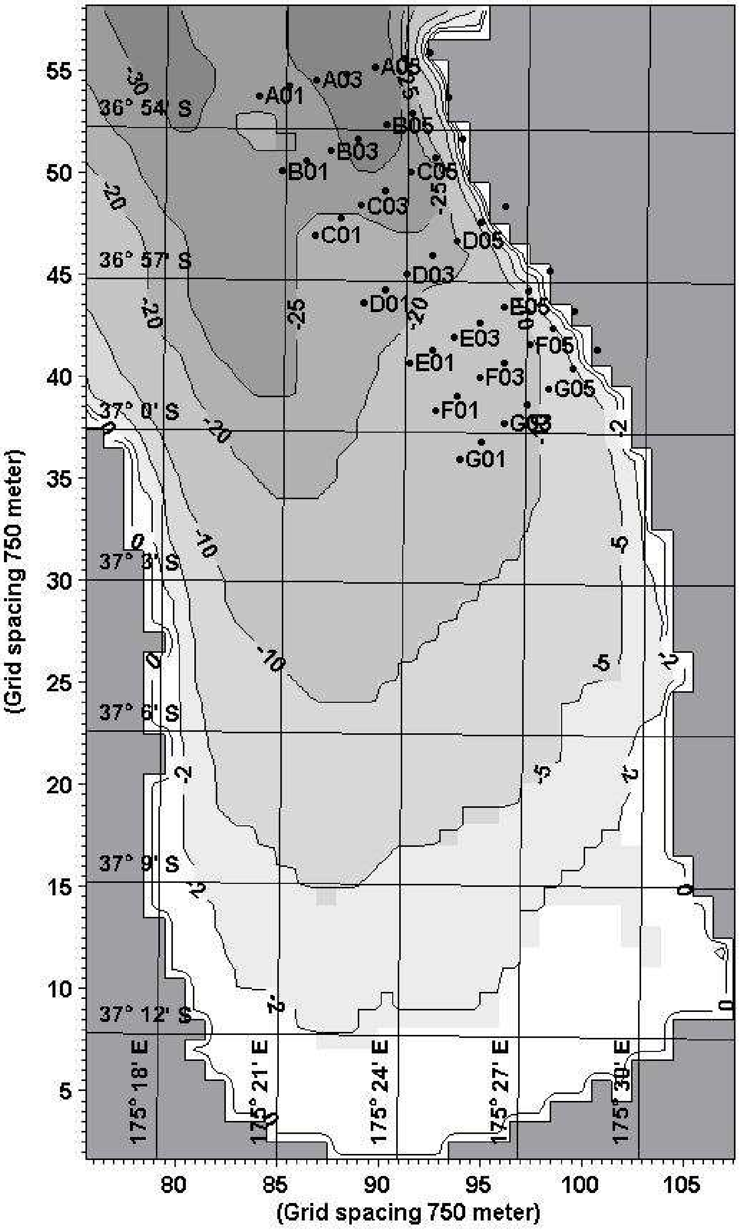
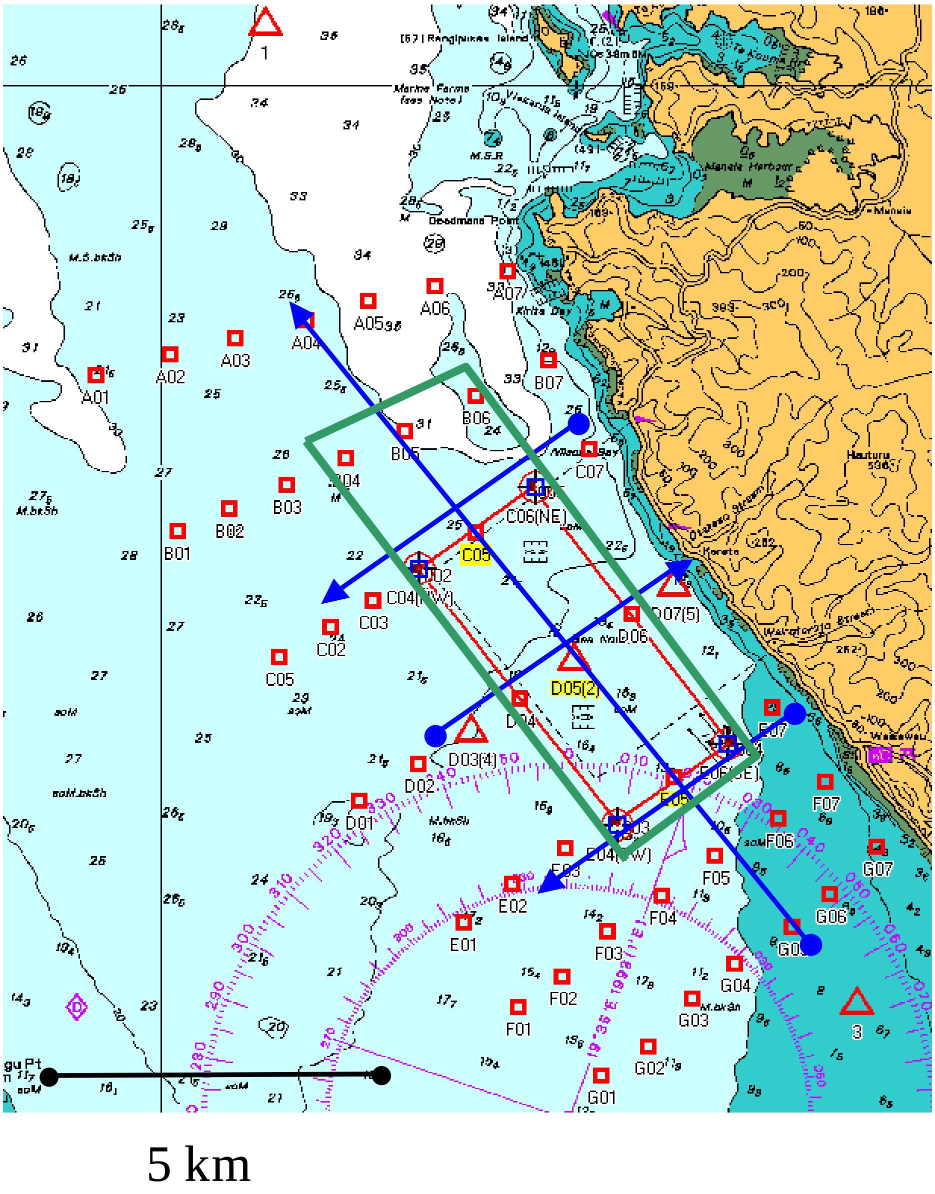


Figure 3

Detailed map of the synoptic survey area. The 49 sampling stations are marked by red squares. The perimeter of Wilson Bay area A is marked by a red rectangle. The green rectangle encloses the stations which were dropped when calculating the surface S_{out}. When calculating the surface S_{perim}, only the perimeter stations (A01, B01 … GO1, GO2, … G07, FO7, … AO7, AO6, … AO1) were used.

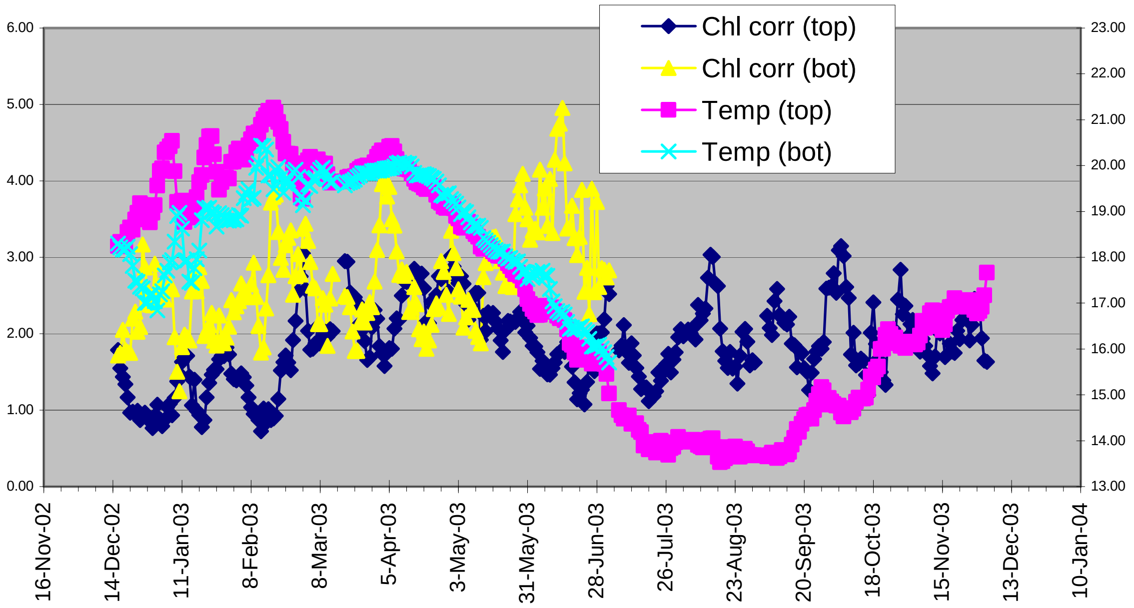


2.5 Environmental conditions around the survey period

Figure 4 presents the time-series of near-surface and deeper water temperature and chlorophyll (inferred from natural fluorescence) measured at a NIWA monitoring station in the northern, central Firth of Thames to the east of Waiheke island. It is immediately apparent that sub-surface chlorophyll concentrations were unusually high during the period of the synoptic survey. A second important feature is also apparent: during the autumn of 2003, near-surface waters and sub-surface waters were of similar temperature and cooled steadily until late May, however the surface waters then cooled rapidly, whilst the deep water stopped cooling for a few days. We believe that this divergence is a consequence of the passage (out of the Firth) of a surface layer 'slug' of cold, relatively fresh water that entered the Firth as runoff from a major rain event (80 mm over 20 & 21 May).

Figure 4

Time series record of temperature and fluorescence measured at NIWA's Firth of Thames mooring site.



Group A's synoptic survey data indicate that, during the survey, dissolved inorganic nitrogen (DIN) concentrations were close to those at which phytoplankton growth might be expected to become nutrient-limited (assuming light and temperature do not limit growth more strongly). DIN concentrations tended to be higher offshore than onshore. In early/mid May dinoflagellates were the dominant members of the phytoplankton community by biomass (Group A, fortnightly monitoring data), however by the time of the synoptic survey their abundance had fallen substantially, whilst that of diatoms had risen. During the survey, diatoms were dominant. The total abundance of the remaining phytoplankton groups held relatively constant through the month.

Figures 5 and 6 illustrate the abundances of three phytoplankton taxa at 25 (of the 49) stations on the first and last day of the synoptic survey (sample collection funded by Group A as part of their synoptic survey, subsequent taxonomic analysis and biomass conversion funded by ARC & EW as part of the contract for this report). Aside from the dominance by diatoms, the second clear feature is that the phytoplankton were most abundant at the south-eastern sampling stations (bottom, left).

Figure 5

Bubbleplot illustrating the relative abundance of the three phytoplankton taxonomic groups on May 25th, 2003 at stations 1, 5 and 7 of each of the seven inshore/offshore sampling transects (A-G) (station A6 is also illustrated). Top figure to bottom figure, the groups are diatoms, 'other taxa', and dinoflagellates. The three polygons represent the perimeters of the three sub-areas of Area A as defined in Figure 1. Bubble sizes are proportional to abundance.

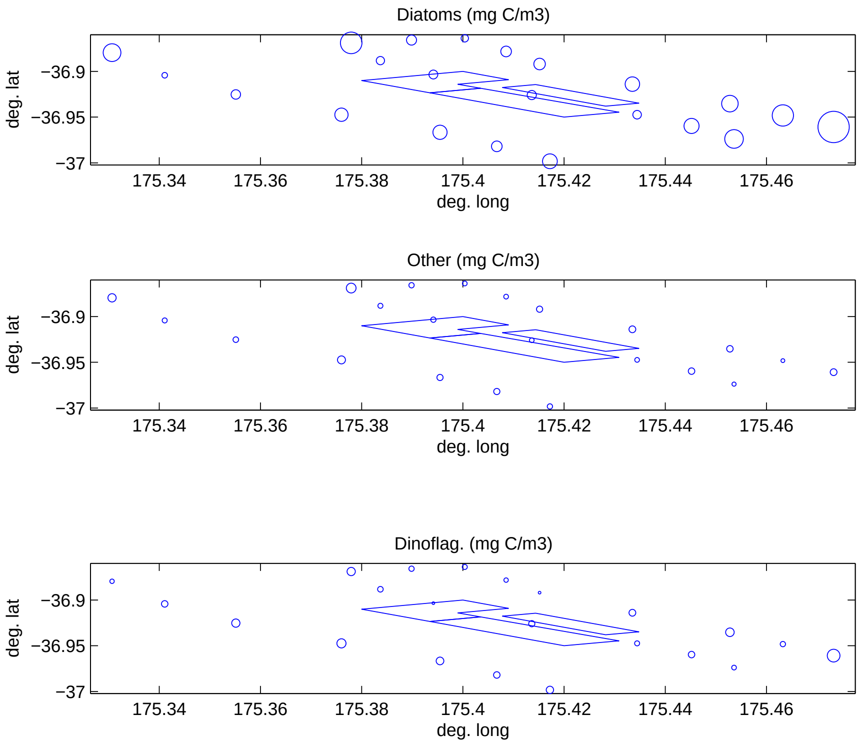
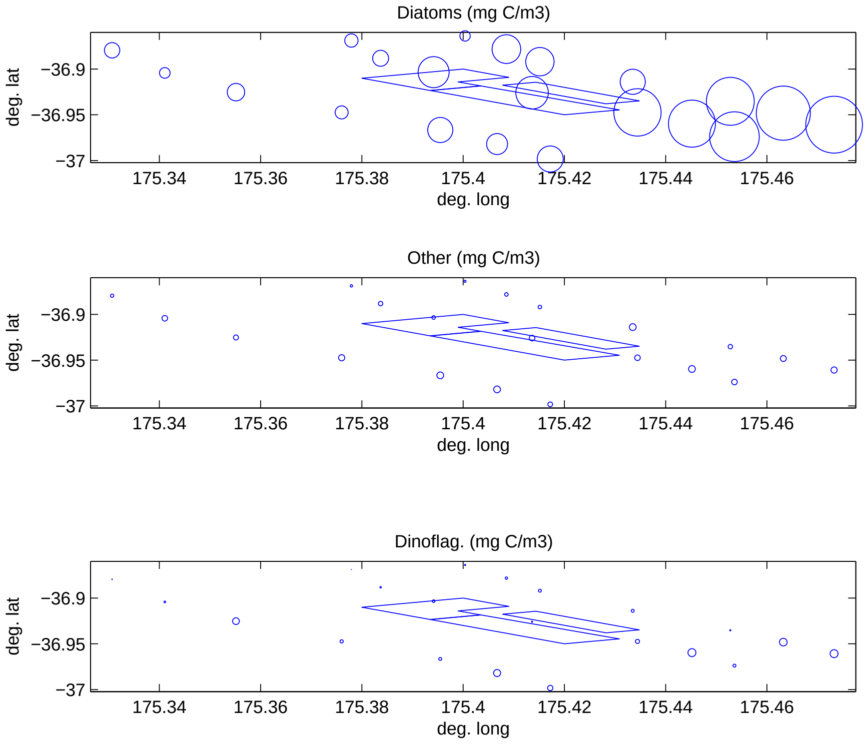


Figure 6

Bubbleplot illustrating the relative abundance of the three phytoplankton taxonomic groups on May 29th, 2003 at stations 1, 5 and 7 of each of the seven inshore/offshore sampling transects (A-G). Top figure to bottom figure, the groups are diatoms, 'other taxa', and dinoflagellates. The three polygons represent the perimeters of the three sub-areas of Area A as defined in Figure 1. Sample collection funded by Group A, subsequent analysis funded by ARC & EW. Bubble sizes are proportional to abundance.



3 Methods (Hydrodynamic model)

3.1 Hydrodynamic model

The hydrodynamic model used in this study was the DHI Water and Environment three-dimensional model MIKE3, an engineering software package containing a comprehensive modelling system for 3D free-surface flows. MIKE3 is applicable to the simulation of hydraulic and related phenomena in coastal areas and seas where stratification or vertical circulation is important. The hydrodynamics are solved on a fixed grid of square cells using the mass conservation equation, the Reynolds-averaged Navier-Stokes equations, including the effects of turbulence and variable density, and the conservation equations for salinity and temperature in three dimensions together with the equation of state of sea water relating the local density to salinity, temperature and pressure.

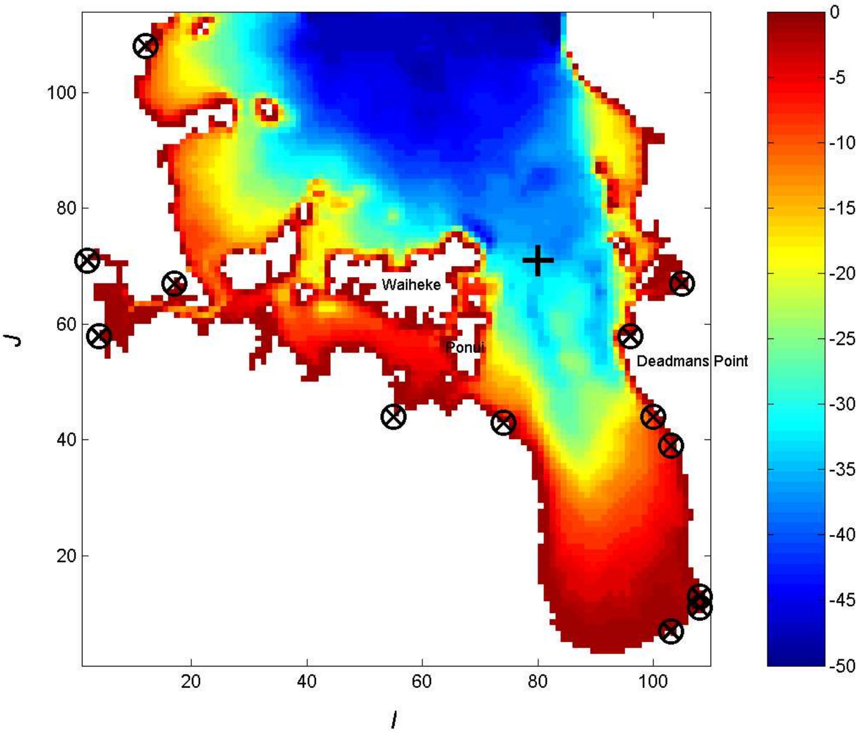
3.2 Model set-up

3.2.1 Bathymetry

This study draws on previous work carried out by NIWA (Stephens, S.A. & Broekhuizen, N. 2003) and uses the Firth of Thames grid to provide hydrodynamic predictions for a plankton depletion model of the Wilson Bay area. The grid consists of 750 m cells - 110 in the east-west direction and 114 cells in the north-south direction. Wet cells on the eastern side of Coromandel peninsula were blocked out since they were irrelevant to the Firth of Thames simulations (Figure 7).

Figure 7

Firth of Thames 750 m bathymetry grid. Colour scale indicates depth (m). River sources are marked ⊗. The NIWA-maintained FoT mooring site is marked +. The *I* and *J* indices on the two axes indicate the grid-cell coordinates (each grid cell is 750 m x 750 m horizontally).



3.2.2 Vertical grid structure

For the Firth of Thames simulations the model used 20 × 2 m-thick vertical layers. The centre of the uppermost layer is 2 m below datum, and the centre of each subsequent layer is 2 m below that. The uppermost layer is therefore 3 m thick, while others are 2 m thick. Water level oscillations, such as tides, cause variations in the thickness of the surface layer. For depths greater than 40 m, the lowermost cell grows to reach the seabed, and for shallower depths layers drop out from the bottom up, with the lowermost layer always greater than 1 m thick.

3.2.3 Turbulence closure

The mixed k-ε/Smagorinsky formulation was employed for this study, using the default parameters. This scheme uses the Smagorinsky formulation in the horizontal and a standard 1-dimensional *k-ε* model in the vertical. This uses transport equations for two quantities to describe the turbulent motion: the turbulent kinetic energy, *k*, and the dissipation rate of turbulent kinetic energy, ε. **Advantages of the mixed scheme are that the** *k-ε* model has well-trialled coefficients that require less calibration, and buoyancy effects are accounted for.

3.2.4 Temperature and salinity dispersion

The dispersion of salinity and temperature is assumed to be proportional to the effective Eddy Viscosity with the factor of proportionality being $1/\sigma_T$, the dispersion factor. σ_T is the Prandtl/Schmidt number. Values of σ_T greater than one imply that diffusive transport is weaker for salt/temperature than for momentum. Dispersion factors of 0.1 and 0.005 were used in the horizontal and vertical directions respectively to account for weaker vertical mixing due to stratification.

3.2.5 Seabed resistance

The default parameter was used. The model is largely insensitive to the bottom friction coefficient in the water depths experienced in most of the Firth of Thames. The region most affected by seabed friction is the shallow southern Firth, where seabed friction will retard the tidal flow. This region is not a critical area for the study.

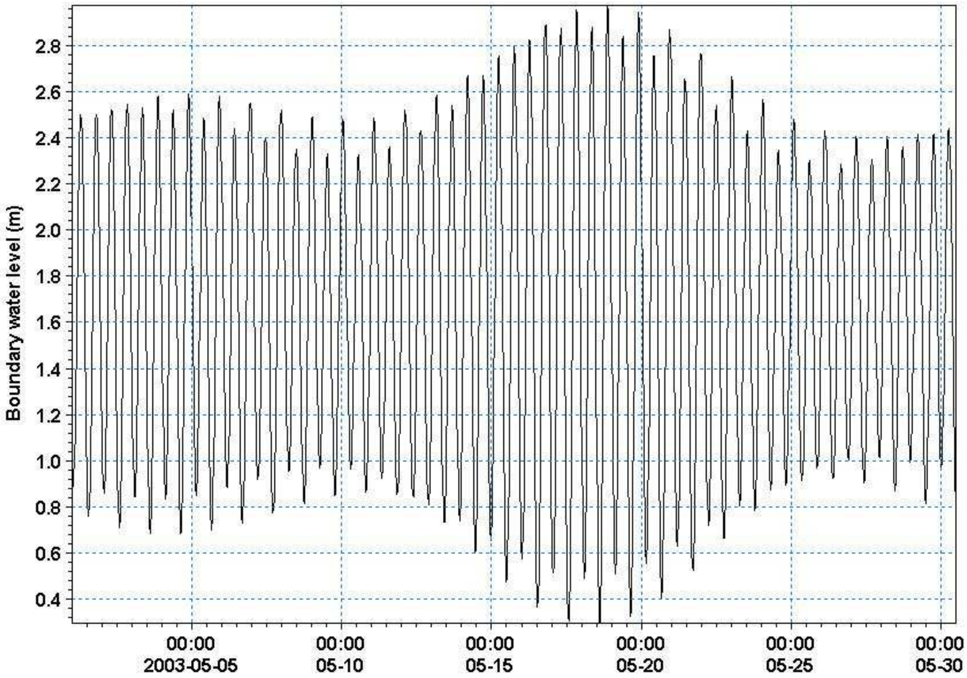
3.3 Forcing inputs to the model

3.3.1 Tide

Tidal water level variations were applied to the open-sea boundaries of the model grid (Figure 8). Both spring and neap tides were represented during the calibration simulations. The period of the synoptic survey (24th - 29th May 2003) follows spring tides and so contain tides in the rang of 2.6-2.8m.

Figure 8

Sea-surface heights (m above Moturiki datum) prescribed at the model's seaward boundary for May 2003. Mean sea level is 1.487 m above Moturiki datum.



3.3.2 Stratification

Stratification occurs when light buoyant water overlies heavy dense water. Stratification is caused either by temperature differences: warm water is lighter than cold water, or by salinity differences: freshwater is lighter than seawater. In winter the Firth of Thames becomes stratified by freshwater runoff from the surrounding catchments, while in summer it becomes temperature stratified as well, by solar radiation and heat exchange with warm air. The summer temperature stratification is generally much stronger than freshwater stratification during winter, although the effect of large floods is unknown.

Stratification does not affect tidal flows much, but the water column response to wind-driven currents can be highly modified by stratification.

The buoyancy force resists vertical change, so a water 'parcel' will tend not to move vertically when the water column is stratified. Therefore, it is much easier for currents to flow horizontally than vertically when the water is stratified. For example, wind-driven surface currents will tend to flow horizontally above the thermocline, and where these currents run into the coast, bottom-return-flows can form flowing in the reverse direction below the thermocline.

Conversely, in unstratified or homogeneous water, there tends to be more horizontal variability and flows are more vertically uniform, as momentum becomes more evenly distributed throughout the water column. Eddies and current jets are more likely to form as wind-driven currents become deflected by the topography. This can lead to complex circulation patterns.

3.3.3 Temperature

Aside from solar radiation inputs at the water surface, the model requires an initial temperature field to be set. It also requires water temperatures to be input at the open boundary at each timestep. Obtaining accurate internal temperature fields is a challenging task because of naturally high spatial variability created by subtleties such as cloud cover. Furthermore, it is practically impossible to measure temperature everywhere on the open boundary to use as input, and initial conditions are often guessed for the same reasons.

Sea surface temperature data from Leigh (Figure 9) were used to define the sea-surface temperature across the open boundary. Data from the NIWA thermistor chain located in the Firth of Thames (Figure 7, Figure 10) were used to obtain the vertical temperature structure for May 2003. This vertical temperature structure was applied to the sea-surface temperatures to obtain the open boundary temperature condition.

River temperatures were specified as 15°C.

Figure 9

Observed daily sea-surface temperatures from Leigh applied to the surface layer of the open boundary.