Regions of Freshwater Influence (RoFI) and the Implications for Sediment Deposition in the Hauraki Gulf

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NASA Landsat 7 Image acquired 27aug2002

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Executive summary

A Region of Freshwater Influence (RoFI) is the coastal zone where there is a dynamically and ecologically significant quantity of lower salinity waters. A marine hydrodynamic model was run over such a domain around the Hauraki Gulf with 20 sources of fresh water, representing the 20 largest river flows in the model domain with the largest annual average sediment loads.

The modelling forms a pilot study designed to evaluate potential use of this approach for the addition of full sediment transport models. As such, the role of this work is to identify what is presently possible and areas for improvement.

The model has been validated by comparison of time-series of simulated temperature and salinity with measurements at the NIWA Firth of Thames mooring as well as for standard large-scale metrics like tides. Despite being a pilot study, the level of agreement is encouraging. Further model development around RoFI behaviour is in progress. This freshwater transport and dilution is a proxy for some aspects of sediment transport. Other aspects of sediment transport pathways remain to be validated.

With regard to sediment transport, the present work suggests future emphasis needs to be placed on wave resuspension, especially in regions like the very south of the Firth of Thames, in order to get reliable results. As a consequence, the primary initial focus here is on the *transport* phase of sediment and using “numerical tracers” to describe the transport of the freshwater that transports the sediment.

1 Introduction

The Department of Conservation's (DOC) Plan Blue framework seeks to understand the impacts that a wide range of land- and marine-based stressors are having on the marine environment. Sedimentation is widely acknowledged as one of the principal threats to the ecological integrity of estuarine and coastal ecosystems. A number of studies have been carried out in New Zealand analysing watershed-originated sediments in rivers and estuaries. However, the extraction of sediment cores in shelf areas has shown that the presence of terrigenous sediments can be tracked to the continental shelf and beyond. This project is a first step towards quantifying the spatial reach of land-originated sediments within the marine environment. We do this by determining the fate of freshwater injected into the coastal ocean by rivers.

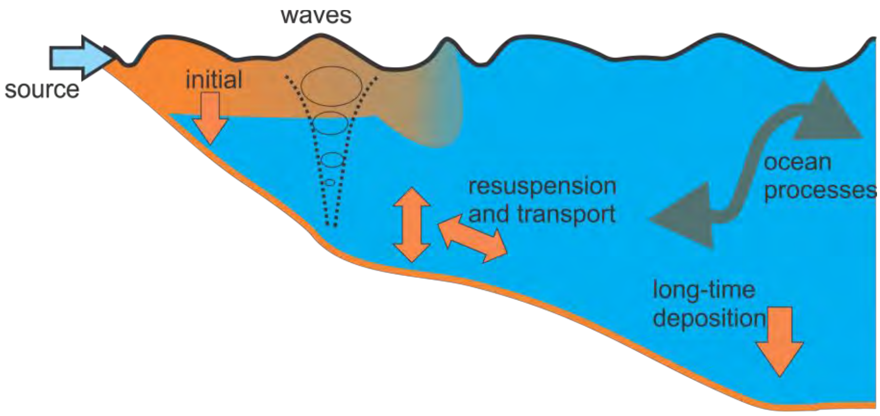


Figure 1: The approach seeks to model the transport of sediment in a coastal zone factoring in sources, modification and deposition. The primary process being considered here though is the buoyant nature of the source waters and its interaction with coastal ocean processes and flows**.**

As described by O'Callaghan and Stevens (2017), "river plumes, or regions of freshwater influence (ROFIs), lie between the shelf seas and estuaries. These regions of the ocean have freshwater buoyancy input that is similar, or greater, in magnitude to the seasonal input of buoyancy as heat over the shelf region (Simpson, 1997). Most broadly, a ROFI is characterized by "horizontal advection of freshwater from the river mouth that defines the shape and character of the plume" (Simpson, 1997; Horner-Devine et al., 2015). There are four main topographic settings—open coast, corner, gulf and gulf with a sill—that may also constrain how freshwater buoyancy inputs are modulated in a ROFI. With a number of possible permutations between boundary forcing and geographic setting a generalized framework describing how momentum and buoyancy transition from source to shelf domain for each ROFI-type remains elusive".

Furthermore, O'Callaghan and Stevens (2017) say "conceptually, buoyant rivers transport suspended land-derived material seaward in surface waters. Material mixes and settles at various points along the plume trajectory. Time-varying events can account for a two-fold increase in residual flows, and are far larger than the 10% typically attributed to residual flows in stratified estuaries. Faster residuals, combined with dynamics being modified for significantly longer (months) than the event itself (days) highlights the need to incorporate transient discharges into conceptual and numerical models to accurately represent physical dynamics and associated material transport in ROFI and coastal systems".

In support of this effort we have conducted a pilot modelling study to provide simulation results suitable for incorporation into the GIS tools. This dovetails with on-going work within NIWA looking at the generalities of quantifying transport of riverine sediment into the coastal ocean. It uses existing information regarding river flows (WRENZ1) and ocean flows around New Zealand (Rickard et al. 2005; Hadfield et al. 2007). This initial focus is on the Hauraki region (Figure 2).

An important requirement for successful modelling at this scale is capturing the regional oceanography at the continental shelf scale. The modelling system uses a nested series of model grids to achieve this.

1.1 The project team

The modelling effort was led by Dr Mark Hadfield. Dr Joanne O'Callaghan provided guidance on aspects relating to available data in the Hauraki region. Dr Mark Pritchard contributed advice on modelling in the region and potential for enhancement for future connection with Plan Blue goals. Dr Craig Stevens oversaw the project. All authors contributed to writing the report. The team has significant experience in modelling and measuring the coastal environment, including river plumes, in New Zealand and internationally as well connecting these results with end-user needs.

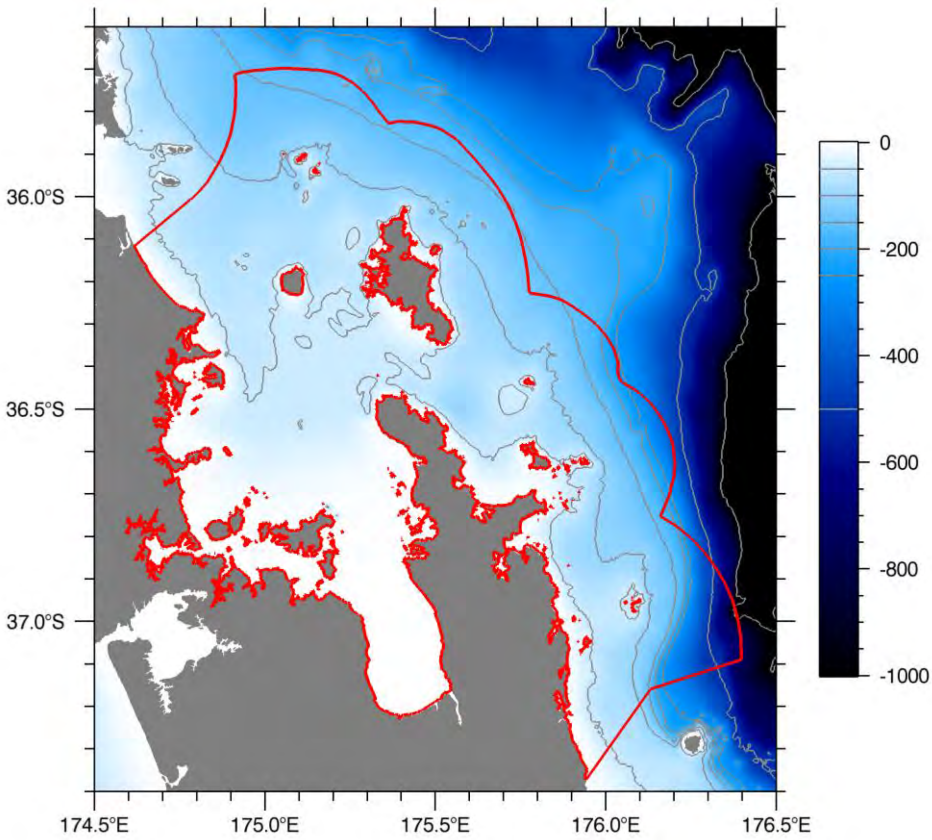


Figure 2: Hauraki Gulf with marine park outlines (Hauraki Gulf Marine Park Act, 2000). Depth in m is shown with colour contours.

[1] http://wrenz.niwa.co.nz

2 Contract Specifications

This report supplies and/or describes:

- Description of model
- Summarised results/outputs
- Illustrative animation in a suitable format for use by DOC
- Discussion of the data validity in the context of available data
- Extension to better link to similar/related tools
- A discussion of the limitations of present approach
- Recommendations for extension/improvement

The essential features required of the present application of the model are:

- 2 years of simulations driven by atmospheric boundary conditions (from numerical weather models), and oceanic general circulation model.
- Nominal 1 km resolution
- Nominal 30 vertical levels.
- At least 10 point-sources for riverine inflow

Specifically, aspects of sedimentation to be explored included:

- Sediment supply based on existing data (annual sediment load).
- sediment size classes with separation to be decided
- Re-suspension of material by wave action to be represented.
- Spatial distributions of two size-class distributions as a sedimentation rate over the region described above.

The objective of the project is to identify a pathway to improved modelling capability around sedimentation rates for the Hauraki Gulf region. Initial simulation results are suitable for usage in spatial mapping tools. It is important to note the "Pilot Study" and "Proof of Concept" nature of the project as identified in the contract (DOC Contract #4397). This states "These services are to conduct a pilot modelling study to provide an initial sedimentation footprint for the HGMP by 30 June 2012. This is a proof of concept study taken as an opportunity to determine the limitations of such an approach and provide recommendations for improving the modelling of sedimentation inputs into the marine environment in the future." In addition, it is important to note that this study preceded on-going work that ultimately will be used to test model "skill" – hence it being a pilot study.

3 Methods

3.1 The modelling system

Understanding ocean transport in the inner shelf zone over long timescales requires a good understanding of regional and sometimes global processes and cannot be conducted in isolation from such scales. A nested set of hydrodynamic model domains was set up for this project (Figure 3). The model used on all three domains was ROMS2 (Haidvogel et al. 2008; MacCready et al. 2009), a

[2] http://www.myroms.org/

widely used, open-source ocean/coastal model. Coupling between the nested domains was one-way and off-line: one-way because each domain influences the smaller-scale domains nested inside it, but not vice versa, and off-line because the models are run separately.

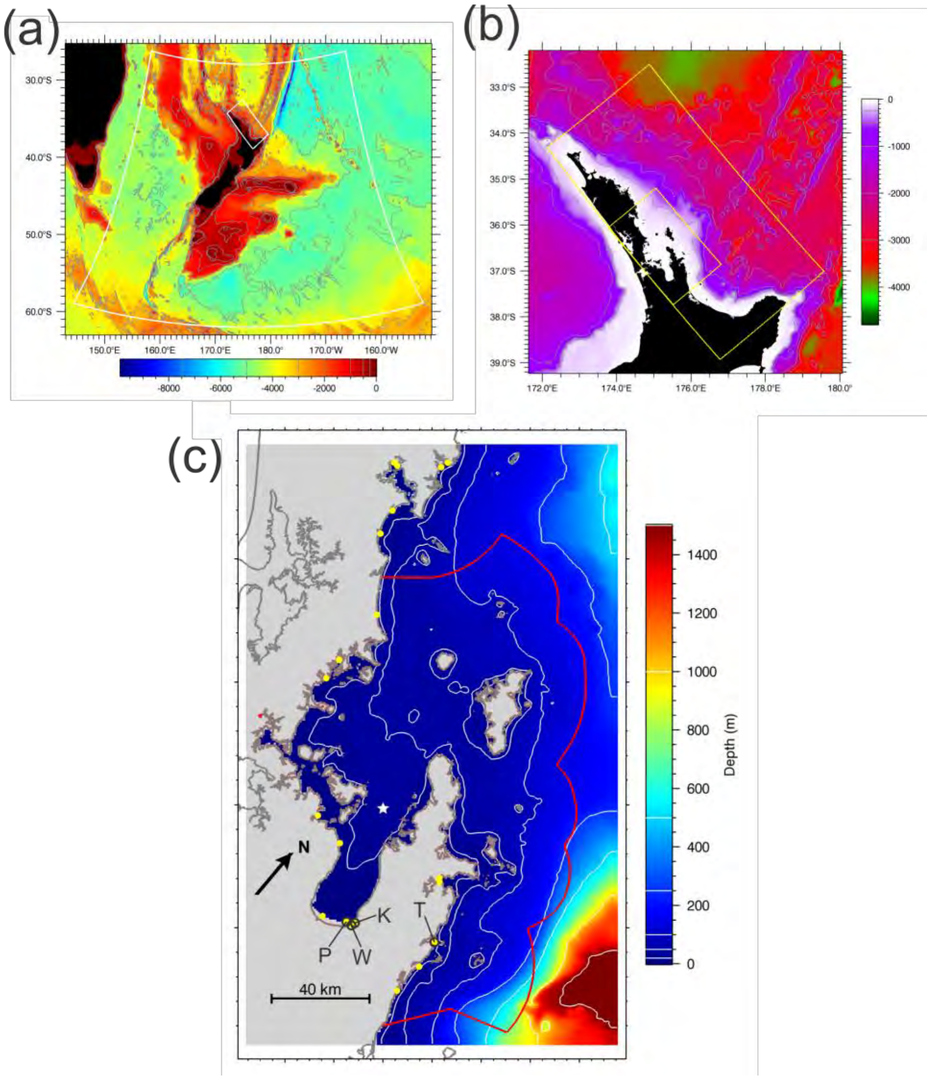


Figure 3: ROMS model domains. **a**) Outer and intermediate model domains; b) Intermediate and inner model domains; c) Inner model domain with model bathymetry (colour plot), coastline (grey), Hauraki Gulf Marine Park outline (red), river locations (yellow circles) and the NIWA Firth of Thames monitoring site (white star, Zeldis et al. 2010). All depths in m. The four major inflows are identified (Waihou, Piako, Tairua and Kaueranga).

Here we build on previous modelling work in the region of Greig and Proctor (1988) and Black et al. (2000). Hadfield and Zeldis (2012) highlight the use of ROMS in the context of freshwater river inputs interacting with the coastal circulation in the Canterbury Bight. The validation of ROMS in this report – and further the more recent work in Hadfield (2013) – shows that the configuration of ROMS being used is able to capture the complex interactions between freshwater fluxes, tides, and winds, and translate the effects consistently into three-dimensional flows. It is these properties we exploit in building the present ROMS implementation.

The outer model simulates the climatological3 large-scale flows around the New Zealand landmass, essentially repeating the work of Rickard et al. (2005), but with a different model code and different forcing datasets. Boundary conditions along the 4 sides of the outer model grid were from a monthly climatology calculated from 10 years' output of a global ocean model (the SODA reanalysis, version 1.4.2, Carton and Giese 2008). The heat, momentum and freshwater fluxes through the sea surface were from the NCEP Reanalysis monthly climatology (Kalnay et al. 1996), with nudging of sea surface temperature (SST) towards a monthly climatology from the NOAA optimum interpolation SST analysis (Reynolds et al. 2002). Weak nudging towards the SODA climatology was applied in the interior of the model to prevent it drifting away from a realistic state. The outer model was spun up from rest for 3 years and then run for several more years, during which time output was saved at 5-day intervals and interpolated spatially to provide lateral boundary data for the intermediate model.

The intermediate model simulates the East Auckland Current and the flows along the continental shelf. The East Auckland Current's mean flow and water mass properties are imposed by the outer model, and the intermediate model adds a much more accurate description of the shelf bathymetry and the ability to generate finer-scale turbulent flow structures (both permitted by the finer grid) along with forcing by real-time, 3-hourly winds from the NIWA NZLAM regional atmospheric model. In the intermediate model these winds act along the entire length of the continental shelf of the north-eastern North Island, from East Cape to North Cape. The resulting wind-driven flows along the continental shelf are, we believe, an important driver of transport in the northern Hauraki Gulf.

The inner domain covers greater Hauraki Gulf at a resolution of 750 m allowing the inner model to simulate the movement of freshwater plumes in reasonable detail. Currents flow through this domain, imposed by the initialisation and boundary data derived from the intermediate model. Like the intermediate model, the inner model is forced by real-time, 3-hourly wind data from NZLAM. Tides were imposed at the boundaries of the inner domain in the form of the six most energetic tidal constituents (M2, S2, N2, O1, K1, & P1) from the NIWA EEZ tidal model (Stanton et al. 2001; Walters et al. 2001). Real-time, 3-hourly wave data were also introduced into the model on the inner domain for calculation of sediment resuspension processes. They were calculated from the output of NZWAVE (Gorman et al. 2003a; 2003b).

While the 750 m grid size is appropriate for coastal embayment-scale processes, it will smooth out some of the near-source details where length scales are relatively small. Furthermore, it will not represent estuarine processes. This has a follow-on effect whereby some important dilution processes may be misrepresented. Further grid refinement can aid this but it becomes prohibitive once many rivers are included.

3.2 Riverine fresh water input

Twenty rivers were represented on the inner domain, fourteen of them inside the boundaries of Hauraki Gulf Marine Park (Figure 3c). Freshwater and sediment inputs from these rivers were taken from the NIWA Water Resources Explorer (WRENZ). To compile the list of rivers, the WRENZ database was scanned for all significant rivers and streams in the area, resulting in a preliminary list of 41 rivers. This list was then sorted in decreasing order of sediment output, with the top 19 selected for input to the model. (Sorting by flow rate would have resulted in a slightly different list,

[3] There is an important distinction between climatological and real-time model forcing—see the glossary (Section 0).

but the top 10 or so would appear in either case.) The rivers are listed in **Error! Reference source not found.**.

Table 1: Rivers represented in the model. Rivers are sorted in decreasing order of sediment input rate.

River name	Location	NZREACH ID	Catchment area km²	Sediment kt/a	Flow m3/s	Conc kg/m3
Waihou	Southern Firth of Thames	3004855	1974.7	151.8	67.3	71.5
Wairoa	Clevedon	2006693	258.2	38.7	4.8	256.2
Piako	Southern Firth of Thames	3005218	1478.8	35.5	22.3	50.6
Waipu	Bream Bay	1023493	217.5	29.5	4.3	217.7
Otaika Creek	Whangarei Harbour	1019667	59.2	20.6	1.2	529.9
Tairua	Coromandel east coast	3003544	223.4	18.4	11.9	48.9
Ngunguru	Ngunguru	1016407	53.0	15.9	1.6	316.0
Waitangi	Horahora	1017042	77.9	15.6	2.0	244.2
Waiwawa	Whitianga Harbour	3002013	191.3	12.8	9.3	43.8
Ruakaka	Bream Bay	1021797	81.9	9.0	1.3	211.7
Mahurangi	Warkworth	2001770	96.9	9.0	2.3	126.8
Raumanga Stream	Whangarei Harbour	1018619	41.6	7.8	0.9	268.7
Whenuakite	Whitianga Harbour	3002120	90.9	7.3	3.9	59.8
Otahu	Whangamata	3006120	71.0	6.7	2.9	72.8
Puhoi	North of Orewa	2002636	47.4	6.1	1.0	195.5
Orere	Orere Point	2006779	43.8	6.0	0.8	252.8
Kaueranga	Southern Firth of Thames	3004591	128.7	6.0	7.2	26.3
Wharekawa	north of Whangamata	3004519	57.0	5.9	2.5	75.9
Pakiri	Pakiri Block	2000655	34.2	5.8	0.8	244.6

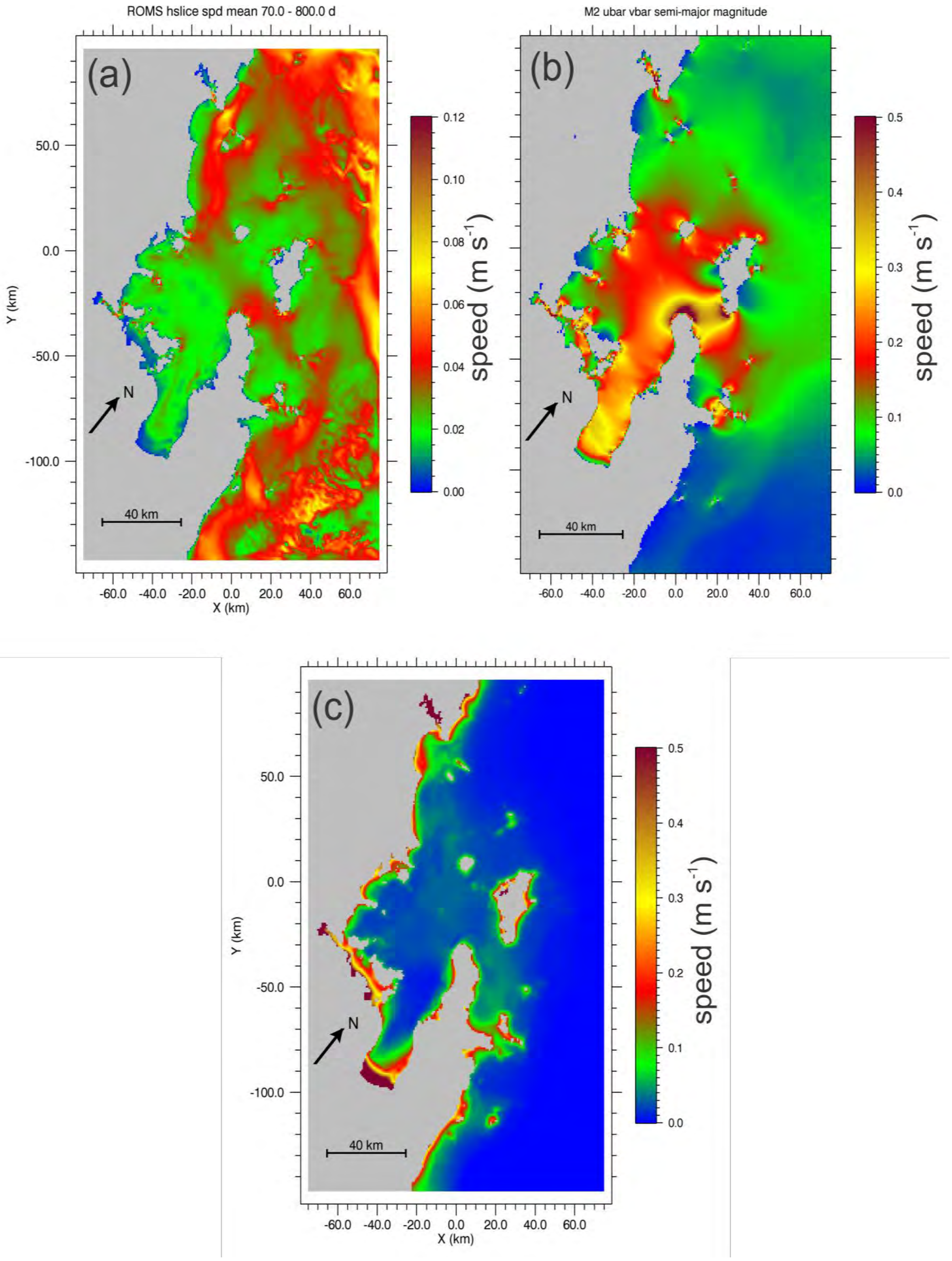


Figure 4: Near-bottom speeds (m s⁻¹) on the inner model domain. (a) Mean non-tidal speed. (b) Maximum tidal speed (semi-major axis) of the main lunar semi-diurnal constituent, M_2. (c) Mean bottom wave orbital speed. Note that figure (a) has a different range on its colour scale from the others and all figures are rotated so that north is to the top right of the panels.

Each river is represented in the model as a source of mass and momentum and is assigned a set of water properties, each of which feeds into the model equations. The salinity of the river water was set to zero, indicating that the river is a source of fresh water. The temperature of the river water was not specified, i.e. it was assumed in the model that the river water had the same temperature as the sea water into which it was being mixed. (This is not strictly true, of course, but is a reasonable assumption given that the temperature of each river is not known). Dynamically (i.e. in terms of density and momentum) the salinity differences are far more important.

The rivers represented were also marked with a tracer (called dye_01) that was given a value of 1 in the river water and 0 in the sea. As that tracer mixes through the domain it acts a measure of the concentration (by volume) of river-derived freshwater. Using this tracer allows us to distinguish river-induced salinity variations from salinity variations due to other processes.

The different panels in Figure 4 represent the average near-bottom speed from each of these contributions and are not exactly comparable (because wave orbital motion, for example, has peak values much higher than the average, whereas the variation in tidal velocity is less extreme) but they suggest that the major process driving sediment resuspension throughout most of Hauraki Gulf is the tidal velocity and the wave orbital motion dominates only in the shallow water, notably near the southern end of the Firth of Thames. The residual (i.e. sub-tidal flow frequencies) water movement is generally much weaker than the tides and so does not contribute significantly.

3.3 Validation data

Validation at the large scale is achieved using the methodologies outlined in recent publicly available reports (Hadfield and Zeldis 2012; Hadfield, 2013). There is an extensive set of data with which we compare the model output for the purpose of validation. That exercise is ongoing and largely beyond the scope of this pilot study report. Measurements (Greig 1990) have been made at an array of stations in Hauraki Gulf (Figure 5; Zeldis et al. 2004).

The observations indicate the importance of wind-driven flows on the continental shelf and longer-period variations in the East Auckland Current further offshore. A mooring has been operated for several years at the NIWA Firth of Thames monitoring site in the northern Firth of Thames (Figure 3c; Zeldis et al. 2010). The data from this site overlap in time with the ROMS simulation described in this report. A comparison between data from a current meter on this mooring and the modelled currents will be done soon. Temperature and salinity time series are available at depths of 11 and 33 m in the mooring and are compared with modelled time series in Section 0.

Mooring data indicate that current speeds in the northern Firth are dominated by tidal oscillations with median speeds of 0.2 m s^{-1}. These currents are in a NW to SE direction making flows aligned to the orientation of the Firth of Thames. Sub-tidal residual flows are an order of magnitude weaker than tidal flows, with speeds at around 0.02 m s^{-1}. These observations are both consistent with model results (Figure 4). Stratification at the monitoring site is dominated by temperature in late spring and summer but temperature becomes vertically uniform through late summer and autumn. During this time, fresh water inputs from autumn and winter discharges cause vertical salinity gradients to dominate stratification in the Firth of Thames.

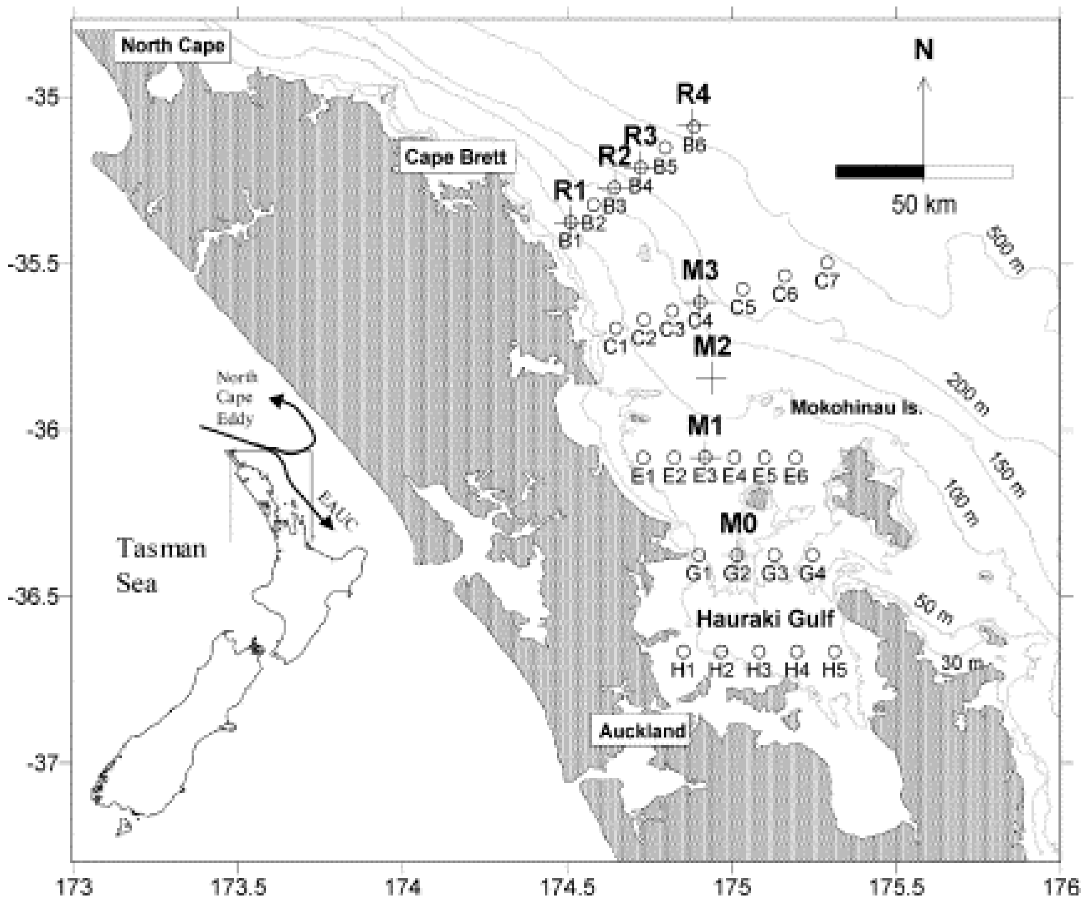


Figure 5: **Stations from Hauraki/Firth observational programme (Zeldis et al. 2004).**

3.4 Simulation set-up

The following sections describe results from a simulation on the inner model domain covering a period of a little more than two years. To generate initial and boundary data for this simulation, the intermediate model was run for several years, starting at 2008-01-01. All times quoted below are relative to this start date. The inner model simulation was initialised at 50 days (2008-02-20) and run to 800 days (2010-03-11).

4 Freshwater Tracer Results

Section 3.4 describes a simulation on the inner domain covering a period of slightly more than two years in 2008–2010. Simulated data fields (including temperature, salinity, velocity and freshwater dye concentration) were stored as 24-hour averaged over consecutive 24-hour intervals (or for a couple of the variables, snapshots at 24-hour intervals).

Surface fresh-water concentration shows discernible plumes extending from the larger rivers and being moved around by the fluctuating surface currents (see animation). The most pronounced plume is associated with the combination of the Waihou, Piako and Kaueranga Rivers in the southern Firth of Thames, with another associated with the Wairoa River east of Auckland. The freshwater plume tends to fill the Firth of Thames and the southern and western Hauraki Gulf. Once fresh water moves into the northern Hauraki Gulf it is dispersed rather quickly.

The graph of time-mean freshwater concentration (**Error! Reference source not found.**) shows values exceeding 1–2% only in the Firth of Thames and southern Hauraki Gulf, with localised plumes also in Whangarei Harbour and Whitianga Harbour. There is no freshwater concentration maximum in Waitemata Harbour, because none of the streams draining into this harbour made the high flow category.

Comparisons were made of modelled time series of temperature and salinity with measurements at the NIWA Firth of Thames monitoring site. The measurements were made at two depths—11 and 33 m—and the modelled data have been interpolated to the same depths.

The modelled and measured temperature time series (Figure 7) have a similar seasonal pattern, with the upper (blue) temperature being higher than the lower (red) temperature from spring through to late summer each year and with an inversion (cool water overlying warmer water) for a brief period in winter. This temperature inversion is possible because stratification in winter is maintained by the salinity profile (Figure 8).   There are annual periods when the field data are isothermal (e.g Figure 7 DOY 100-190, 450-550). However, these are not directly matched with periods of zero salinity difference (Figure 8) so the water column is mostly stratified throughout the year.

The thermal variations also capture some of the shorter-term processes, notably the pauses in summer warming around year 1 and year 2. The fact that the modelling captures the deeper step in temperature around year 2.1 is important as this means the model is doing more than simply reproducing surface fluxes.

The salinity comparison is not as good. Both model and observations suggest static stability and evidence that salt compensates for the brief periods of thermal instability in winter. The simulations also do reasonably well with the deep salinity. Where the comparison breaks down is in the upper salinity where the model is clearly struggling to capture the surface layer dynamics. In the measurements the 11-33 m difference is highest in the winter and spring; in the model the difference tends to be highest in summer. The mismatch in this respect between model and measurements probably arises because the input of freshwater from the rivers in the model does not vary seasonally (in fact it does not vary at all). The model generally produces somewhat smaller vertical differences in temperature and salinity than the measurements: this may indicate that vertical mixing in the model is somewhat too strong, or it may result from the lack of a seasonal variation in river input or possibly biases in the model's surface fluxes.

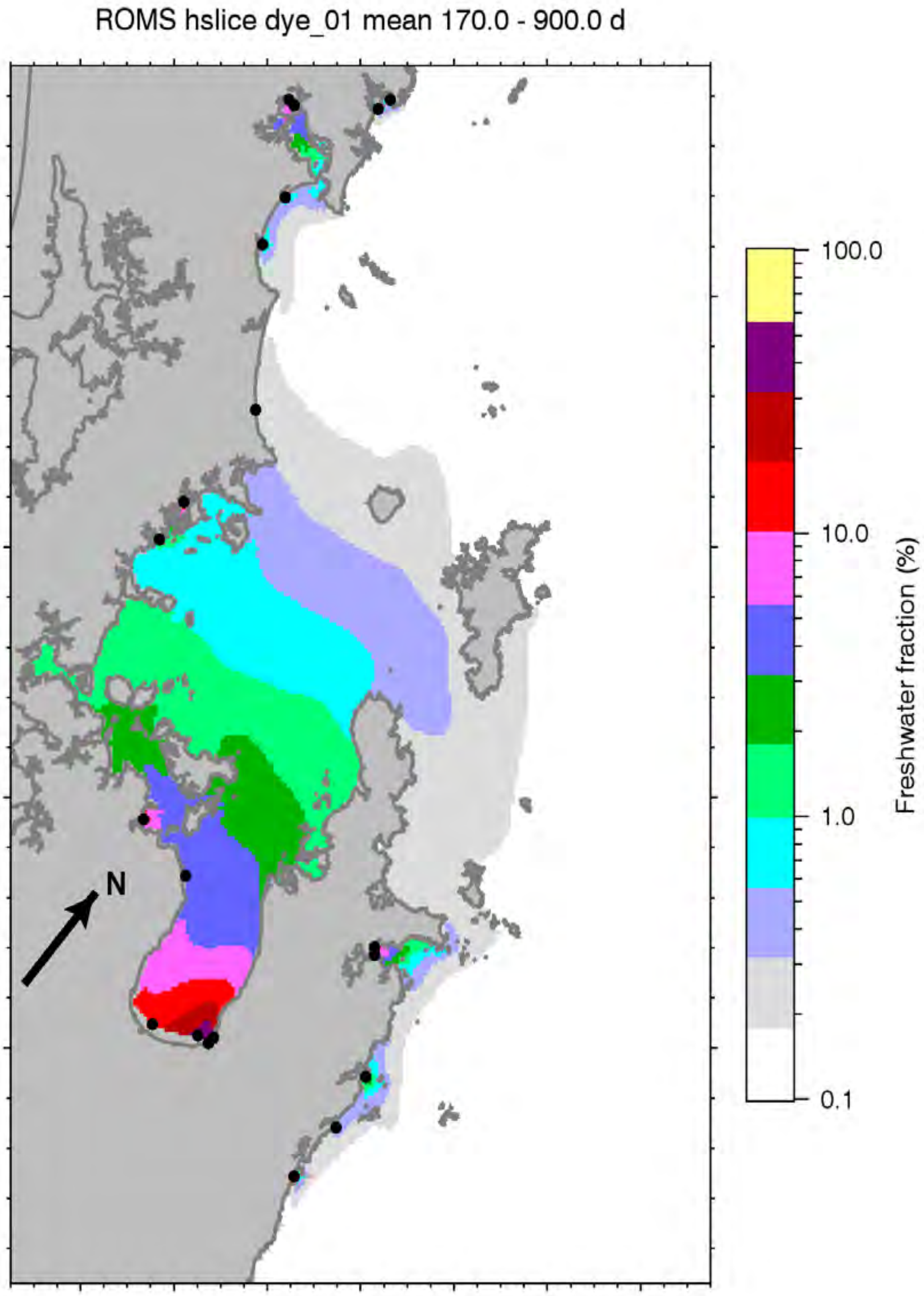


Figure 6: Time-mean surface freshwater concentration from the Hauraki Gulf model. The mean is evaluated over a two-year period (t = 170 d to t = 900 d) for the simulation described in Section 3.4. Note the log10 colour scale.

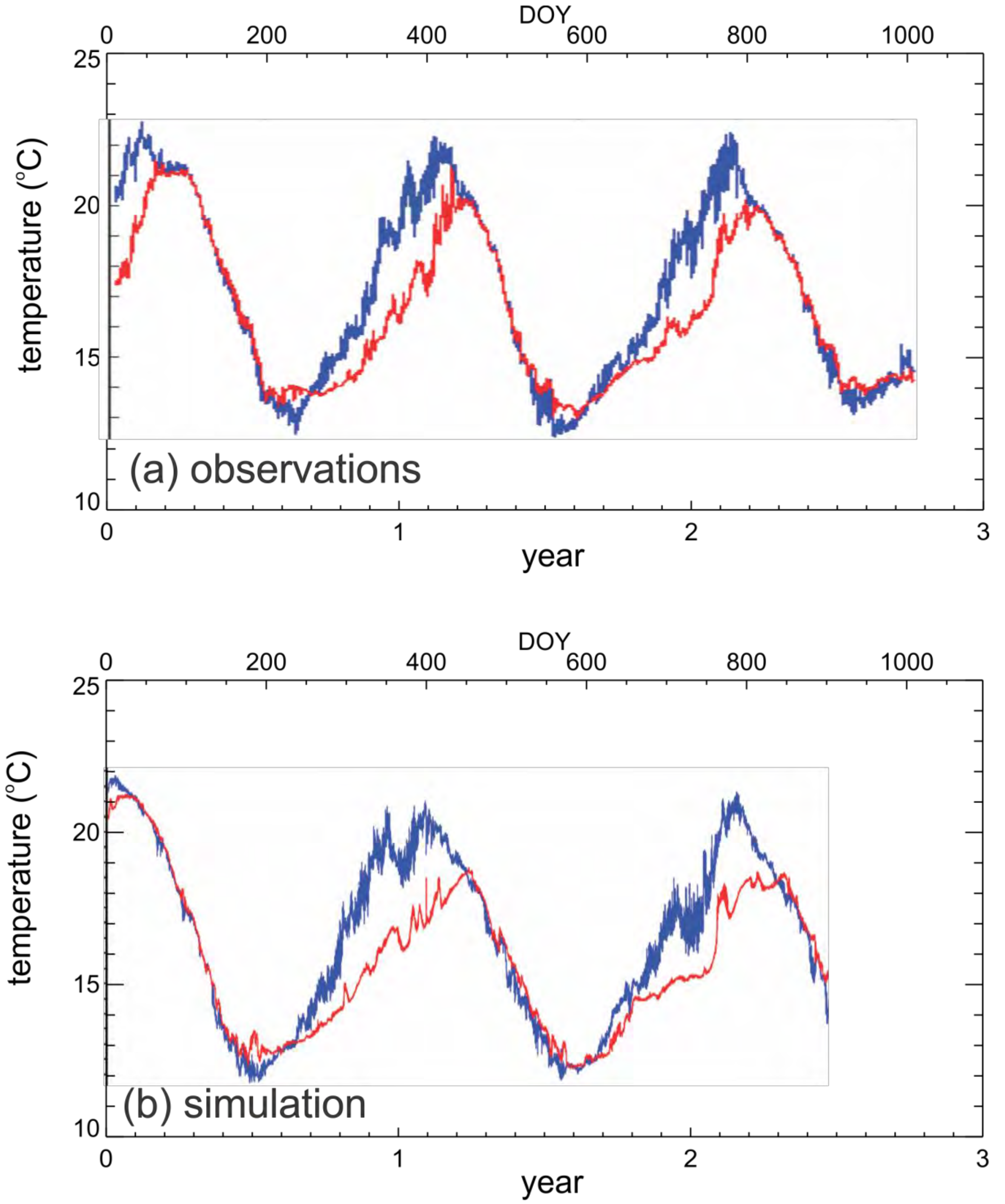
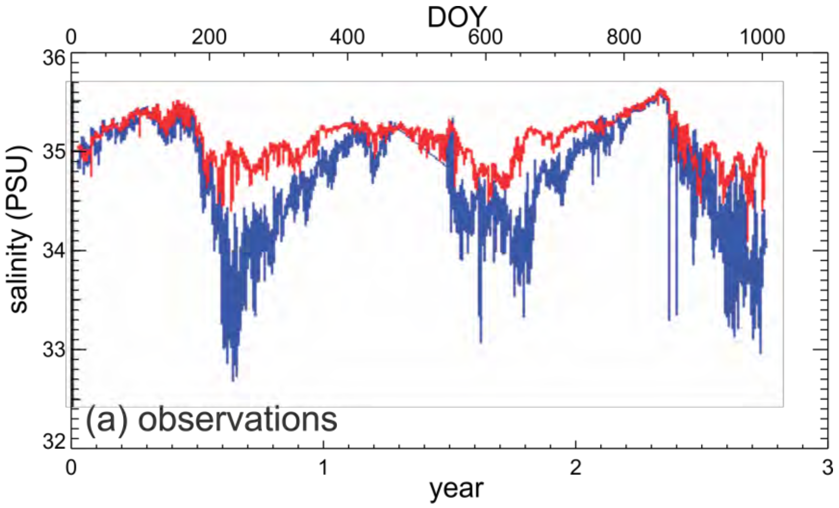


Figure 7: (a) Observed and (b) modelled temperature at the Firth of Thames monitoring site over the day of year (DOY). The traces represent temperatures at depths of 11 m (blue) and 33 m (red). The timeseries start at Jan 1, 2008.



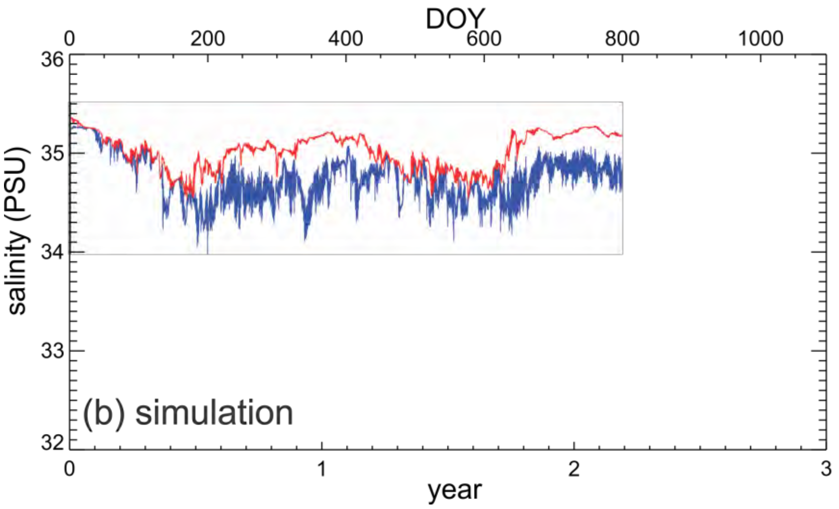


Figure 8: (a) Observed and (b) modelled salinity at the Firth of Thames monitoring site. The samples are for depths of 11 m (blue) and 33 m (red). The timeseries start at Jan 1, 2008.

5 Adding Sedimentation

Whereas the fresh water introduced in the river plumes is buoyant and therefore tends to be concentrated near the surface, suspended sediment tends to sink and be concentrated near the bottom. Simulations can follow surface and bottom suspended sediment concentration which appear as suspended sediment plumes similar in some respects to the freshwater plumes, but generally less spatially extensive and with higher concentrations at the bottom than the surface. Such distributions are one potential measure of the impact of riverine sediment on the marine system, as suspended sediment has effects on the biota, both directly (smothering) and indirectly (via effects on light levels and visibility). SSC (mass) in itself is not an accurate measure/predictor of visual water clarity or light penetration. These optical properties depend also on particle characteristics (size, shape, colour) and organic components (CDOM, Phytoplankton etc.). Another indicator of the impact of sediment is the thickness of deposited sediment. This section describes the setup of a sediment model for tracking suspended and seabed sediments. It remains to validate these simulated distributions and so the sediment results are not shown. Rather, we focus on the steps undertaken in setting up a “proof of concept” model and the future work required to enable applied modelling of sediments in the region.

In the trial simulations where sediment transport is considered, each river is assigned a constant suspended sediment concentration equal to the value in the right-hand column of Table 1. The ROMS parameterisations for sediment and associated quantities (e.g. bottom boundary layer, wave forcing) are described by Warner et al. (2008). The model accepts a series of user-defined sediment classes, each characterised by several properties such as grain size, grain density, settling velocity and threshold shear stress. Typically, a continuous distribution of sediment particle sizes in reality is represented in the model by several sediment classes, each with a different grain size.

The sea bed in this suite of simulations has been represented in simple terms, as medium-fine sand. This means that it cannot represent transport of seabed sediments accurately: the sea bed in this model is provided primarily as a substrate in which riverine sediments can be retained.

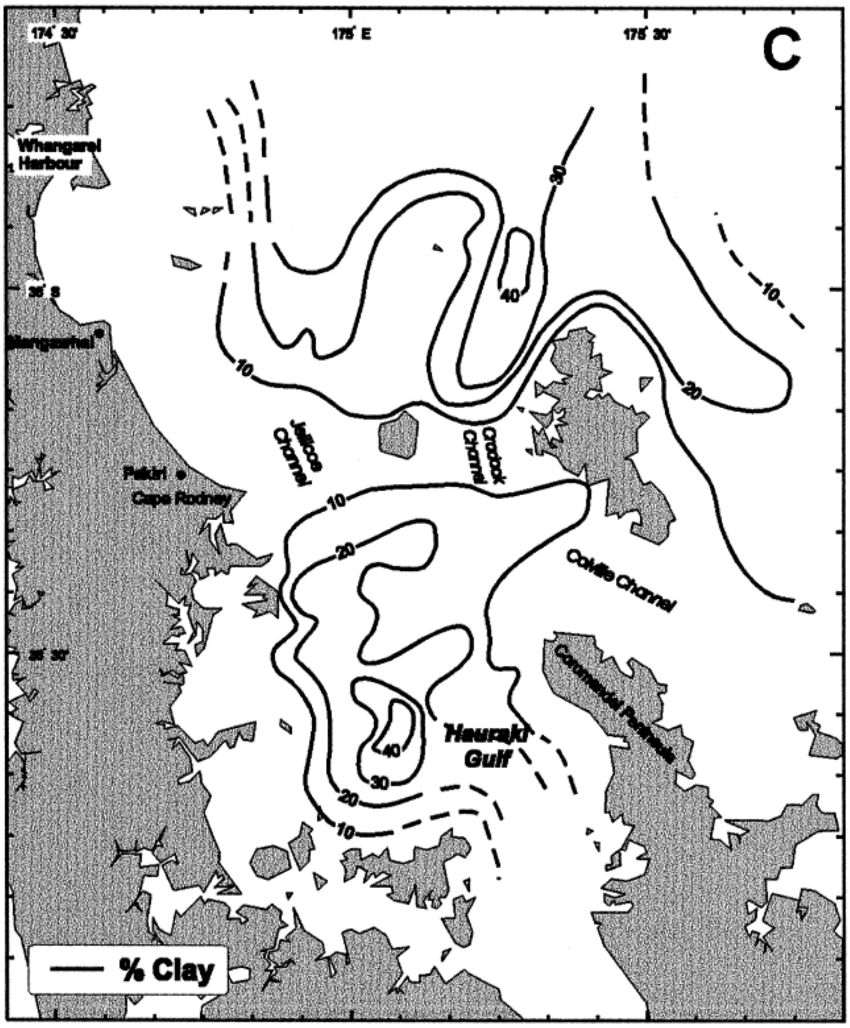


Figure 9: **Reproduction from Fig. 3c of Manighetti and Carter (1999) showing weight percentage of clay.**

At the bottom of the water column there is a multi-layer sediment bed, each layer being composed of a mixture of the sediment classes. The top bed layer exchanges sediment vertically with the lowest level in the water column. The model optionally allows horizontal exchange of bed material between neighbouring grid cells (a process called bedload transport) but this was not turned on for the present simulations.

The thickness of the bed layers is adjusted at each model time step according to the scheme described by Warner (2008), within any changes resulting in mass-conservative exchange between the layers. At the beginning of each time step an active layer thickness is calculated (Warner et al. 2008, Equation 21; Harris and Wiberg 1997, Equation 1). The active layer thickness sets a minimum for the top bed layer thickness, meaning that sediment is immediately mixed over this depth, and this is important in regulating the availability of fine sediment in the bed for erosion.

For the simulations described below the total sediment bed thickness was set initially to 0.5 m, with four layers. Initially the thickness of each layer was 0.125 m, but this adjusted after the first time step. Incidentally, the ROMS model optionally allows for the depth at the base of the water column to be adjusted as the total sediment bed thickness changes, but this facility was turned off for the present simulations.

Vertical exchange of sediment between the top bed layer and the water column is the sum of two terms (Warner 2008, Equation 22). The first is deposition, which occurs continuously and is calculated separately for each sediment class as the product of the near-bottom concentration and the settling velocity. The second is erosion (Warner 2008, Equation 23; Ariathurai and Arulanandan 1978, which occurs only when the bottom stress exceeds a critical value, user-specified for each class.

Bottom stress is calculated with the Sherwood, Signell and Warner bottom boundary layer formulation (Warner et al. 2008, Section 3.7), which requires data on the height, period and direction of surface wind waves. For the present study this data was taken from NZWAVE. Biological effects on deposition/resuspension rates (i.e. flocculation, etc.) were not taken into consideration.

Given that the expense of running the model increases rapidly with the number of sediment classes, and that the information on the different sediments in the wider Hauraki Gulf system is very limited, for this pilot modelling study a series of trial simulations was run, each with a small number of sediment classes (1–3) to establish the minimum set of classes and properties that gives plausible behaviour. The classes that we finally settled on are given in **Error! Reference source not found.**. Other properties required by ROMS include default erosion rate parameter (2×10^{-4} kg m^{-2} s^{-1} for all classes) and a default porosity (0.4 for all classes).

The different contributions to the near-bottom water movement that determines the bed shear stress, and hence the rate of resuspension, are indicated in Figure 4. The contributions are the tidal and residual currents—both represented explicitly in the model—and the wave orbital motion—which is calculated in the model based on surface wave data, with an allowance for the reduction in orbital velocity with depth. This wave component is reduced in mangrove areas but this is beyond the present scope.

Table 2: Sediment classes and properties. Settling velocity and threshold shear stress were calculated from the class mid-point grain size using formulas from van Rijn (1984) and Soulsby (1997) with a grain density of 2650 kg m^{-3} (characteristic of quartz).

Name	variable name	Source	Grain size	Settling velocity		Threshold stress
			(μm)	(mm/s)	(m/d)	(N/m²)
Coarse silt	sand_01	Rivers	23	0.37	32.0	0.069
Fine silt	sand_02	Rivers	6	0.02	1.7	0.024
Fine–medium sand	sand_03	Seabed	250	30.8	2660	0.179

6 Discussion

6.1 Hydrodynamics evaluation

Validation of the hydrodynamic simulation is on-going (some of which appeared in O'Callaghan and Stevens 2017), however the results are clearly plausible and the comparison with temperature and salinity time series at the Firth of Thames monitoring site is encouraging. This validation will be extended in future by comparison with measured currents from the monitoring site and also with data from the array of Hauraki Gulf instruments (Figure 5).

The validity of the sediment results remains uncertain. Given the relatively fine spatial resolution of the model (grid size 750 m) the simulations have been limited to ~2.5 years in length. This makes it possible to carry out meaningful simulations of only the fine sediments, namely silts and clays. The coarser sands and gravels have much longer residence times in Hauraki Gulf than can be treated in the present modelling approach. The sea bed in this simulation has been represented in very simple terms, as medium-fine sand. This means that it cannot represent transport of seabed sediments accurately: the sea bed in this model is provided primarily as a substrate in which riverine sediments can be retained.

Manighetti and Carter (1999) surveyed the sediment distribution and dispersal processes in Hauraki Gulf, with their treatment of dispersal concentrating on sands. The figure in their paper that is most comparable with the current results is their Figure 3c (reproduced here as **Error! Reference source not found.**), showing the clay percentage in the sediment deposits. They see a maximum in the south-central Hauraki Gulf, north of Rangitoto, Motutapu and Waiheke Islands. The most likely explanation for deposition to be enhanced there is that tidal currents are relatively weak (Figure 4b). Manighetti and Carter's Figure 3c also shows a maximum in the northern gulf, between Whangarei Harbour and Great Barrier Island and the present model does not agree with this. Manighetti and Carter do not show data from the deeper water at the edge of the continental shelf, where our model shows accumulation.

There is a considerable amount of work (Swales et al. 2007) showing accumulation of sediment and shoreline advance in southern Firth of Thames. The present model does show deposition in the Firth of Thames generally, but with a minimum within a few kilometres of the southern shoreline. Possibly this is likely to result from the wave orbital velocity (which is interpolated from NZWAVE data) being overestimated. There are other possible explanations also - sediment-transport processes in the southern Firth are complex (e.g., cohesive muds dynamics including flocculation, bed evolution/consolidation/shear strength, bed-forms, onshore mud transport by waves, wave attenuation at high SSC, flux convergence etc.), which can't readily be simulated by a single/constant sediment load over 1-2 years.

The work described in this report was a pilot study, with several significant limitations:

- river inputs of fresh water assumed constant;
- near-source effects and stratification processes not well resolved due to relatively coarse spatial resolution and generic buoyancy terms;
- The sedimentation work was particularly challenged;
  - river inputs of sediment was assumed constant;
  - riverine suspended sediment concentration specified very simply (two size classes);
  - a relatively simple model for near-bottom wave orbital velocity.
  - biological effects on deposition/resuspension rates (i.e. flocculation, etc.) were not taken into consideration.

We recommend that distribution of these results maintain reference to the limits of the study terms of reference which are restated as "these services are to conduct a pilot modelling study to provide an initial sedimentation footprint for the HGMP by 30 June 2012. This is a proof of concept study taken as an opportunity to determine the limitations of such an approach and provide recommendations for improving the modelling of sedimentation inputs into the marine environment in the future."

6.2 Recommendations for future work and additional data products

More observations are required, particularly of near-bottom suspended sediment concentration and deposition/erosion processes.

An improved wave model, e.g. SWAN (Booij et al. 1999) would allow higher spatial resolution and a better representation of the bathymetry, and this should improve predictions of near-bed orbital velocity, which would be particularly valuable in southern Firth of Thames.

A more thorough comparison of model output with existing data is on-going at the time of writing. This has a particular focus on the water column salinity stratification (O'Callaghan & Stevens, 2017). In addition, skill analysis for currents and salinity will give some measure of model performance as well as improve confidence in the future sediment transport model which is largely being driven by the flow.

Time-varying river input is crucial, both for flow and sediment input. A survey of available data is the first step. Data on time-varying sediment input is likely to be scarce, but one can make considerable advances with simple flow-load relationships. TOPNET models of all major rivers discharging to the Hauraki Gulf – Firth of Thames system and fringing estuaries is being implemented as part of the multi-agency MBIE CCII Climate Adaption project (Law et al. 2017).

The trade-off between model spatial resolution and simulation length could be shifted. One could move in the direction of longer simulations with a coarser resolution model, or shorter simulations with a finer-resolution model (or both), depending on the specific requirements. Part of this aspect is the nature of the resuspension, bringing the sediment to a location is only part of the result. It is important to also determine the likely residence time.

It would be desirable to develop remotely-sensed ocean colour products (from MODIS AQUA archives held by NIWA) for suspended sediments (to directly track sediment plumes) and for coloured dissolved organic matter (as freshwater tracers). An example image is included in the frontispiece of this report. These data can also be processed as statistical products describing plume behaviours in space and time.

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8 Glossary of abbreviations and terms

climatological	In connection with model forcing, an adjective describing data (frequently at one-month intervals) with an annual cycle that is repeated indefinitely, thus representing generic conditions, cf. real-time.
domain	In mathematics, the set of mathematical entities (points) where a function is defined. In geophysical modelling, the spatial region covered by the model grid.
EcoConnect	An environmental forecasting system developed by NIWA.
ESRI	A geographic data company which distribute the dominate GIS tool ARCGIS
GIS	Geographic Information System – a set of protocols for describing spatial information. This does not typically represent explicit time variations or mechanics hence the need for process-based ocean models.
NCEP reanalysis	This is a best-knowledge global dataset of geophysical ocean-atmosphere properties.
MODIS Aqua	The Moderate Resolution Imaging Spectroradiometer is an instrument aboard the earth orbiting satellite Aqua. Aqua passes south to north over the equator in the afternoon.
Nesting	Driving a model domain with a larger model domain
NetCDF	A data format suited for dissemination of large model datasets.
NZLAM	A NIWA-operated weather prediction model
NZWAVE	A NIWA-operated wave prediction model.
real-time	In connection with model forcing, an adjective describing a dataset representing a sequence of actual dates and times, cf. climatological.
ROMS	An ocean simulation tool developed by the ocean modelling community. It has a number of versions and can be applied at a range of scales.
SSC	Suspended sediment concentration
SST	Sea surface temperature. Often derived from satellite, care must be taken as this temperature will not be representative of the bulk ocean temperature as in most cases the ocean is temperature stratified.

9

10 References

Ariathurai, R; Arulanadan, K.; 1978. Erosion of cohesive soils. Proc. Am. Soc. Civil Eng., J. Hydraul. Div., 104:. 279–283.

Black, K.P.; Bell, R.G.; Oldman, J.W.; Carter, G.S.; Hume, T.M. (2000). Features of 3-dimensional barotropic and baroclinic circulation in the Hauraki Gulf, New Zealand. New Zealand Journal of Marine and Freshwater Research 34(1): 1–28.

Blott, S.J.; Pye, K. (2001). GRADISTAT: a grain size distribution and statistics package for the analysis of unconsolidated sediments. Earth Surface Processes and Landforms 26(11): 1237–1248.

Booij, N.; Ris, R.C.; Holthuijsen, L.H. (1999), A third-generation wave model for coastal regions, Part I, Model description and validation, Journal of Geophysical Research 104(C4): 7649–7666.

Carton, J.A.; Giese, B.S. (2008). A reanalysis of ocean climate using simple ocean data assimilation (SODA). Monthly Weather Review 136(8): 2999–3017. doi:10.1175/2007MWR1978.1

Gorman, R.M.; Bryan, K.R. and Laing, A.K. (2003a) Wave hindcast for the New Zealand region - deep water wave climate. New Zealand Journal of Marine and Freshwater Research 37(3): 589–612. doi:10.1080/00288330.2003.9517191

Gorman, R.M.; Bryan, K.R. and Laing, A.K. (2003b) Wave hindcast for the New Zealand region: nearshore validation and coastal wave climate New Zealand Journal of Marine and Freshwater Research 37(3): 567–588. doi:10.1080/00288330.2003.9517190

Greig, M.J. (1990). Circulation in the Hauraki Gulf, New Zealand. New Zealand Journal of Marine and Freshwater Research 24(1):141–150. doi: 10.1080/00288330.1990.9516409

Greig, M.J.; Proctor, R. (1988). A numerical model of the Hauraki Gulf, New Zealand. New Zealand Journal of Marine and Freshwater Research 22(3):379–390. doi: 10.1080/00288330.1988.9516309

Hadfield, M.G; Zeldis, J.R. 2012: Freshwater dilution and transport in Canterbury Bight, NIWA Client Report WLG2011-54: 39 pp.(http://ecan.govt.nz/publications/Reports/freshwater-dilution-transport-canterbury-bight.pdf)

Hadfield, M.G. 2013: South Taranaki Bight iron sand extraction sediment plume modelling (Phase 3 Studies), NIWA Client Report WLG2013-36: 86 pp.(www.epa.govt.nz/Publications/NIWA_sediment_plume_modelling_report.pdf)

Hadfield, M.G.; Rickard, G.J.; Uddstrom, M.J. (2007). A hydrodynamic model for Chatham Rise, New Zealand. New Zealand Journal of Marine and Freshwater Research 41: 239–264. doi: 10.1080/00288330709509912

Hadfield, M.G.; Uddstrom, M.J.; Goring, D.G.; Gorman, R.M.; Wild, M.; Stephens, S.A.; Shankar, U.; Niven, K.; Snelder, T.H. (2002). Physical variables for the New Zealand Marine Environment Classification System: development and description of data layers. NIWA Client Report No.CHC2002-043.

Haidvogel, D. B., H. Arango, W. P. Budgell, B. D. Cornuelle, E. Curchitser, E. Di Lorenzo, K. Fennel, W. R. Geyer, A. J. Hermann, L. Lanerolle, J. Levin, J. C. McWilliams, A. J. Miller, A. M. Moore, T. M. Powell, A. F. Shchepetkin, C. R. Sherwood, R. P. Signell, J. C. Warner, and J. Wilkin, 2008: Ocean forecasting in terrain-following coordinates: Formulation and skill assessment of the Regional Ocean Modeling System. Journal of Computational Physics,227, 3595-3624.

Harris, C.K.; Wiberg, P.L. (1997). Approaches to quantifying long-term continental shelf sediment transport with an example from the Northern California STRESS mid-shelf site. Continental Shelf Research 17(11): 1389–1418. doi: 10.1016/S0278-4343(97)00017-4

Hauraki Gulf Marine Park Act 2000. http://www.legislation.govt.nz/act/public/2000/0001/latest/viewpdf.aspx.

Horner-Devine, A. R., Hetland, R. D., and MacDonald, D. G. (2015). Transport and mixing in coastal river plumes. Annu. Rev. Fluid Mech. 47, 569–594. doi: 10.1146/annurev-fluid-010313-141408

Kalnay, E.; Kanamitsu, M.; Kistler, R.; Collins, W.; Deaven, D.; Gandin, L.; Iredell, M.; Saha, S.; White, G.; Woollen, J.; Zhu, Y.; Leetmaa, A.; Reynolds, R.W.; Chelliah, M.; Ebisuzaki, W.; Higgins, W.; Janowiak, J.; Mo, K.C.; Ropelewski, C.; Wang, J.; Jenne, R.; Joseph, D. (1996). The NCEP/NCAR 40-Year Reanalysis Project. Bulletin of the American Meteorological Society 77(3): 437–471. doi:10.1175/1520-0477(1996)077<0437:TNYRP>2.0.CO;2

Law, C.S., Rickard, G.J., Mikaloff-Fletcher, S.E., Pinkerton, M.H., Behrens, E., Chiswell, S.M. and Currie, K., 2017. Climate change projections for the surface ocean around New Zealand. New Zealand Jour. Marine and Freshwater Research. doi.org: 10.1080-00288330.2017.1390772

MacCready, P., N.S. Banas, B.M. Hickey, E.P. Dever, and Y. Liu (2009): A model study of tide- and wind-induced mixing in the Columbia River Estuary and plume. Continental Shelf Res., doi:10.1016/j.csr.2008.03.015.

Manighetti, B.; Carter, L. (1999). Across-shelf sediment dispersal, Hauraki Gulf, New Zealand. Marine Geology 160(3–4): 271-300. doi: 10.1016/S0025-3227(99)00024-9

O'Callaghan, J.M. and Stevens, C.L., 2017. Evaluating the Surface Response of Discharge Events in a New Zealand Gulf-ROFI. Frontiers in Marine Science, 4, p.232.

Reynolds, R.W., N.A. Rayner, T.M. Smith, D.C. Stokes, and W. Wang, 2002: An improved in situ and satellite SST analysis for climate. J. Climate, 15, 1609-1625.

Rickard, G.J.; Hadfield, M.G.; Roberts, M.J. (2005). Development of a regional ocean model for New Zealand. New Zealand Journal of Marine and Freshwater Research 39(5): 1171–1191. doi: 10.1080/00288330.2005.9517383

Simpson, J. H. (1997). Physical processes in the ROFI regime. J. Mar. Syst. 12, 3–15. doi: 10.1016/S0924-7963(96)00085-1

Soulsby, R. (1997). Dynamics of marine sands. Thomas Telford Publications, London. 249 pp.

Stanton, B.R.; Goring, D.G.; Bell, R.G. (2001). Observed and modelled tidal currents in the New Zealand region. New Zealand Journal of Marine and Freshwater Research 35(2): 397–415. doi:10.1080/00288330.2001.9517010

Swales, A.; Bell, R.G.; Ovenden, R.; Hart, C.; Horrocks, M.; Hermanspahn, N.; Smith, R.K. (2007). Mangrove-habitat expansion in the southern Firth of Thames: sedimentation processes and coastal hazards mitigation. NIWA Client Report HAM2006-138, Environment Waikato Technical Report 2008/13, 65 p.

van Rijn, L.C. (1984). Sediment Transport, Part II: Suspended Load Transport. Journal of Hydraulic Engineering 110: 1613–1641.

Walters, R.A.; Goring, D.G.; Bell, R.G. (2001). Ocean tides around New Zealand. New Zealand Journal of Marine and Freshwater Research 35(3): 567–579. doi:10.1080/00288330.2001.9517023

Warner, J.C.; Sherwood, C.R.; Signell, R.P.; Harris, C.K.; Arango, H.G. (2008). Development of a three-dimensional, regional, coupled wave, current, and sediment-transport model. Computers & Geosciences 34(10): 1284–1306. doi: 10.1016/j.cageo.2008.02.012

Warner, J.C.; Armstrong, B.; He, R.; Zambon, J.B. (2010). Development of a Coupled Ocean-Atmosphere-Wave-Sediment Transport (COAWST) Modeling System. Ocean Modelling 35(3): 230–244. doi:10.1016/j.ocemod.2010.07.010

Warner, J. C., W. R. Geyer, and J. A. Lerczak, 2005: Numerical modeling of an estuary: A comprehensive skill assessment. J. Geophys. Res., 110.C05001, doi:10.1029/2004JC002691

Zeldis, J.R., Walters, R.A., Greig, M.J.N., Image, K. (2004). Circulation over the northeastern New Zealand continental slope, shelf and adjacent Hauraki Gulf, during spring and summer. Continental Shelf Research, 24: 543–561. doi: 10.1016/j.csr.2003.11.007

Zeldis, J.R.; Stewart, C.; Walkington, M.; Bind, J.; Diettrich, J. (2010). NIWA Firth of Thames monitoring mooring data summary for proposed fish farming zone evaluation. NIWA Client Report No.CHC2010-134.