Report to the Environment Committee 16 October 2014

Purpose

1. To present to the Committee the hydrodynamic model report for the Queen Charlotte Sound.

Background

2. Council contracted NIWA to develop hydrodynamic models of the Queen Charlotte Sound (QCS) and Pelorus Sound. This report deals with the QCS model.

3. A hydrodynamic model simulates water movement from tides, wind and residual currents. NIWA has developed a 3 dimensional model which models changes in the temperature and stratification of the water column over seasonal and annual periods.

4. The model has also been linked with water quality (nutrients) and ecological (phytoplankton and zooplankton) processes. NIWA has tested the model with several scenarios related to the effects of existing and new fish farms on Queen Charlotte Sound and Tory Channel.

5. The Council's water quality monitoring data collected monthly over the last three years was used to help calibrate the hydrodynamics and water quality modelled patterns.

6. NIWA presented a progress report to the Committee in May 2014. The final report has now been received. The report runs to 183 pages, so only the 5 page Executive Summary is **attached**.

Comments

Robustness of model

7. The model was produced by three NIWA scientists: Drs David Plew, Niall Broekhuizen and Mark Hadfield. It was peer-reviewed by Ben Knight of the Cawthron Institute prior to the Council receiving it.

8. The Cawthron review described the model as acceptable in its attributes and performance. However, like all models, refinements are recommended to better understand the dynamics of particular areas where finer-scale modelling would be beneficial, such as for Tory Channel.

9. A subsequent paper to the Committee will outline potential future development work once the recommendations have been considered for this model, and the Pelorus model once completed.

Hydrodynamic findings

10. The model revealed that Tory Channel is an efficient pump or "mixing pipe" exchanging water between Cook Strait and QCS (Figure 1). Large tidal flows through Tory Channel allow for exchanges of water (and nutrients) between central QCS and Cook Strait.

11. These tidal fluxes range in volume from ~20,000 m^3s^{-1} to ~30,000 m^3s^{-1} during the monthly tidal cycle, keeping the waters in Tory Channel well-mixed in the water column throughout the year.

12. In addition, there is a sub-tidal flow of cooler and more saline water from Tory Channel into inner QCS. The sub-tidal flows join the prevailing estuarine circulation pattern in QCS. Cooler, deeper water from outer QCS also flows into the inner sound, which is then transported to the outer QCS as warmer surface waters out in a clockwise direction around Arapawa Island.

13. Interestingly the volume of water coming through (the much smaller) Tory Channel is much larger during each tide than through the outer QCS entrance.

14. The Inner and Outer QCS are stratified in summer (warmer waters in surface layer). Flushing times vary as a result, with flushing occurring more quickly in summer as warmer waters are replaced by upwelled deeper water from Tory Channel. Residence times of water were estimated as being up to 35-46 days in the inner QCS and 11 days in Tory Channel.

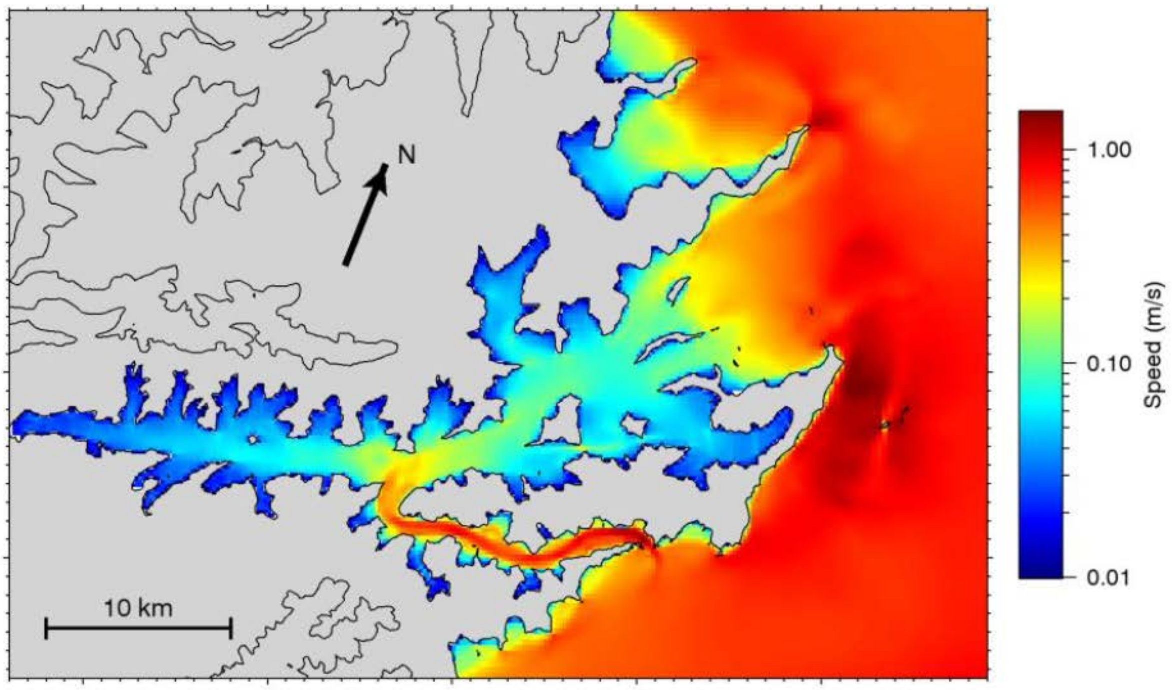

Figure 1: Model of mean current speed based on one year's hourly data. The colour chart reflects the relative speed of the current in a log scale, with the red colour 100 times faster than the dark blue.

Biophysical model

15. A biophysical model attempts to figure out how nutrients interact with plankton. This is relevant as excessive nutrients can cause plankton to increase to levels where algal blooms may result. Algal blooms can also occur naturally due to temperature stratification in the water column, and long water residence times. For example, this occurs in Opua Bay in Tory Channel from time to time.

16. Nutrients originate from upwelling from coastal shelf formations, the effects of aquaculture and/or land-use. In the Marlborough Sounds, nitrogen is the only element that might limit biological activity. Nitrogen is naturally at low levels in the Sounds, so it is limiting to plankton growth. At certain times of the climate cycle, such as in El Nino, more nutrient-rich upwelling occurs due to favourable wind conditions from the NW forces colder waters into the Sounds. A consequence of this is faster mussel growth.

17. It is when nutrient levels significantly exceed these normal fluctuations that would be concerning. This is called a 'trophic change', which is another way of saying that conditions at the base of the food chain have been fundamentally altered. This would be evident in much more frequent algal blooms, discoloured murky water, and a likely reduction in fish life from changes to the food chain.

18. This is one of the reasons Council undertakes regular state of the environment water quality monitoring. The time series of the data collected (since 2011) has also proved also very useful for modelling the scenarios of increased nitrogen discharge.

19. NIWA ran three model scenarios to better understand the effects of nitrogen originating from existing mussel farms, and from new and existing fish farms. The effects of the Picton waste-water discharge were also included in the model, but non-point source catchment discharges after rainfall were excluded as monitoring had shown the level of nutrients was lower than occurring in seawater.

20. The scenarios also looked at different ways nitrogen may or not may not be available to plankton through sediment chemistry processes. This is because nitrogen is cycled in different forms through the sediments and water column. For example, the effects of denitrification processes were simulated, which is where nitrogen becomes biologically unavailable in seafloor sediments

21. Scenario 1 modelled QCS as if there was no aquaculture but with denitrification. Scenario 2 was also without aquaculture but without denitrification. Scenario 3 modelled the effects of all existing and new fish (and mussel) farms without any loss of nitrogen.

22. The key take home message from the report is that the effects of new and existing fish farms are within the bounds of natural variability. In other words, the modelled discharge of nitrogen is unlikely to cause any long-term negative ecological effects. NIWA's opinion is that the combination of winter-time light limitation, relatively rapid-flushing, and seabed denitrification make it unlikely that the present levels of fish farming will result in a trophic change of nutrient over-enrichment.

Next steps

23. The NIWA report makes a number of recommendations for further work to improve the model. These will need to be carefully considered to ensure the Council's investment in the model is maximised. A report back to the Committee will be made sometime in early 2015.

24. A key goal is to make the model accessible for industry and the community. Council's contract with NIWA means that future scenarios (as opposed to further development work) can be run at a nominal cost. Once the Pelorus model has been completed, Council and NIWA will run a workshop with industry and interested members of the community. This is to ensure that the capability and limitations of both the QCS and Pelorus models will be more widely understood.

25. The report in its entirety will be made available on Council's website. However, given that it is a complex technical document, a public summary will be developed. The feasibility of having interactive animations on Council's websites to improve accessibility will also be examined.

Summary

26. NIWA has now delivered the contracted hydrodynamic-biophysical model for Queen Charlotte Sound. The Cawthron Institute has peer-reviewed it and assessed it as an acceptable and defensible model. The underlying circulation patterns in QCS have been identified. The model tests scenarios including current future effects of fish farms on the ecology of the Sounds. NIWA conclude the permitted level of fish farming is unlikely to cause a trophic change to the ecosystem. A work programme is shortly to get underway to consider the recommendations of the report for further development work, and to make the model more accessible for industry and the community.

NIWA
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A biophysical model for the Marlborough Sounds

part 1: Queen Charlotte and Tory Channel

Prepared for Marlborough District Council

September 2014

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NIWA CLIENT REPORT No:	chc2014-116
Report date:	August 2014
NIWA Project:	MDC13301

Executive summary

The Marlborough District Council commissioned NIWA to undertake biophysical modelling of the Queen Charlotte and Pelorus Sounds. The purpose of the modelling was to describe effects of existing and proposed mussel and fish farms on water quality. This report presents results from the Queen Charlotte Sound and Tory Channel. Results for the Pelorus Sound will be presented in a subsequent report.

The biophysical model consists of a three-dimensional hydrodynamic model (with 20 layers in the vertical) coupled to a biogeochemical model (which models water quality, plankton, and other biological and chemical attributes). We used the ROMS hydrodynamic model coupled with the Fennel biogeochemical model, with additional components added to simulate mussel and fish farms. The biogeochemical model includes: (a) the inorganic nutrients ammonium and nitrate, (b) a single phytoplankton class, (c) a single zooplankton class and (d) two classes of particulate organic detritus (slow and fast sinking). The abundances of most of these are characterized by means of nitrogen concentration, but the phytoplankton is characterized by two variables: nitrogen concentration and chlorophyll concentration.

Three farming/biogeochemical scenarios were modelled:

- *Present day/existing farms scenario*: mussel farms in operation in 2010 (counted by aerial-surveys), and New Zealand King Salmon Ltd. Salmon farms that operated during 2012/2013.
- *Approved farms*: as for the *present day* scenario, but also including the one newly approved salmon farm in Tory channel (*Ngamahau*) and mussel farms which have been approved (or which existed, but were not occupied) at the time of the aerial survey.
- *Worst case*: as for *approved farms*, but ignoring the losses of nitrogen from the marine system that arise from denitrification. The *present day* and *approved farms* scenarios both assume that 75% of any particulate organic nitrogen (from any source) which settles to the bed will be lost from the system through denitrification (whilst the remaining 25% is returned to the water column as ammonium). In the *worst-case* scenario, none of the sedimenting particulate organic nitrogen is lost from the system. It is all returned to the water column as ammonium.

Additional scenarios were modelled with *no farms* and with *mussel farms only* in order to provide a baseline for assessing farm impact, and for comparing the relative influence of mussel farms and fish farms.

Simulations spanned 500 days (24 May 2012 to 6 October 2013), consisting of a 135 day spin-up period followed by 365 days (1 year) over which the model outputs were analysed.

Horizontal grid resolutions from 50 m to 400 m were tested. Finer resolution grids provide greater detail of the spatial distributions of both physical (hydrodynamic) and biogeochemical properties, but the simulations take significantly more time to run (halving the size between grid points increases the computation time by a factor of approximately 8). The 200 m model reproduces the essential aspects of the hydrodynamics of Queen Charlotte Sound with acceptable accuracy and allows simulations with the full biophysical model for periods of over one year. The 200 m resolution grid was used when making the biophysical simulations reported within this document.

The hydrodynamic model was compared to current meter data from Tory Channel and Outer Queen Charlotte Sound. Modelled temperature and salinity are compared with time-series measured at two depths from these sites and also in Inner Queen Charlotte Sound, as well as with monthly profiles of temperature and salinity collected by Marlborough District Council.

Analysis of the hydrodynamic model output allows us to make the following conclusions about the physical behaviour of the Sound.

- The Inner and Outer Queen Charlotte Sound exhibit a seasonal stratification, while Tory Channel remains well mixed year round.
- The tidal volume fluxes through Tory Channel are large, at around 20,000 m^3s^{-1} at neap tide and 30,000 m^3s^{-1} at spring tide. The large tidal flows through Tory Channel maintain a vertically well-mixed state and allow it to act as a conduit for bi-directional exchange between central Queen Charlotte Sound and Cook Strait.
- There is a sub-tidal flow, typically inwards through Tory Channel and outwards through the outer Queen Charlotte Sound (i.e. clockwise around Arapawa Island) that varies from extremes of -2000 m^3s^{-1} to +6000 m^3s^{-1}. Short term (5-10 day) fluctuations in this flow are largely driven by wind, with winds from the SSW driving a positive (clockwise around Arapawa Island) flow. This sub-tidal inflow through Tory Channel will aid the movement of water from Cook Strait into central Queen Charlotte Sound.
- The sub-tidal flow described above averaged over the final year of the simulation is 660 m^3s^{-1} but there is a slow variation between less than 500 m^3s^{-1} in winter to 1800 m^3s^{-1} in early autumn. This variation does not appear to be related to wind, but might be related to the seasonal variation in temperature and salinity.
- The model produces a well-defined estuarine circulation in Queen Charlotte Sound consistent with observations from mooring data from the Outer Queen Charlotte Sound. No estuarine circulation is seen in Tory Channel.
- Particularly in summer, Tory Channel water is cooler and more saline – and hence denser – than surface water in the Queen Charlotte Sound. Tory Channel water will therefore tend to move into the lower, inflowing layer of the estuarine circulation in Queen Charlotte Sound and move into the inner Sound before it is transported outward at the surface through inner and outer Queen Charlotte Sound.
- The flushing behaviour of Queen Charlotte Sound has been investigated with idealised tracer sources in three locations. Flushing time is an indication of how long it takes for water within a region to be replaced. The flushing time (Table 3-2) varies from 35–46 days for tracer released in Inner QCS to only 10.9 days for tracer released in central Tory Channel. The flushing time for the tracers released in Inner and Outer QCS varies seasonally, being larger in winter than summer, owing to a seasonally varying estuarine circulation taking surface water out of the Sound.

We calibrated the biophysical model against three years of water-quality data which have been collected from five stations in the Marlborough Sounds by Marlborough District Council. The calibrated model reproduces the annual average water-quality characteristics at all stations very well. It also reproduces the amplitude of the annual phytoplankton cycles well, but at the two inner-most stations (in Inner QCS), it suggests that the phytoplankton have a single (mid-summer) abundance maximum. In contrast, the field data suggest that there are two maxima during the year, in late winter/early spring and in late summer/early autumn. In Tory Channel and outer Queen Charlotte (where the farms are, and where the farm effects are likely to be most marked) the model reproduces the phase of the seasonal cycles better. There, however the model shows peak phytoplankton abundance in early/mid-summer, whereas the field data show it occurs in late summer/early autumn.

Under the assumption that benthic denitrification removes 75% of all sedimenting particulate organic nitrogen, the biophysical model predicts that:

- Mussel farming induces bay-scale effects where the concentrations of phytoplankton and detritus decrease whilst the concentration of ammonium tends to be elevated. These effects amount to a few percent (up to circa 15%) of *background* concentrations. In summer, the remineralized ammonium from the mussels can stimulate moderate (a few percent) increases in phytoplankton and detrital abundances in the far-field (beyond the bays in which the farms are found).

- Fish farming induces effects which extend through the entire Queen Charlotte/Tory channel system during the summer, but are of more limited spatial extent during winter. Except very close to the farms, the effects do not exceed 20% of background in summer (30% in winter). These are smaller than natural variability.

- The majority of the farm-derived nutrient is predicted to be lost from the system by export to Cook Strait rather than by denitrification in the seabed.

In simulations when we assumed that there is no denitrification in the *worst case* scenario) (i.e. that all sedimenting particulate organic nitrogen is returned to the water column as ammonium), the model shows:

- *no-farms, no denitrification* – summertime phytoplankton concentrations increase by a margin of approximately 10% (outer Queen Charlotte) – 40% (inner Queen Charlotte) relative to the *no-farms+denitrification* baseline. Summertime zooplankton concentrations increase by a margin of 20–100%.

- *approved mussel and fish farms, no denitrification* – summertime phytoplankton increase by margins of 20-60% (relative to *no farms with denitrification*) whilst zooplankton increase by 50-300%. Changes (of smaller magnitude) are also evident in the concentrations of nutrients and detritus.

Given that denitrification is a benthic process, the fact that the relative changes in concentrations tend to be greatest in the shallow side bays and shallow inner Queen Charlotte is not surprising.

Whilst the model does predict that fish farming will yield increased nutrient and phytoplankton concentrations, the resultant elevated concentrations are not alarmingly high. They are not atypical of New Zealand coastal waters and the time-averaged simulated concentrations do not exceed levels that have been measured in the Sounds on some occasions. Similarly, whilst mussel-induced plankton depletion is larger than we initially anticipated, we do not regard it as alarmingly severe.

The changes in nutrient and plankton concentrations are small in comparison to natural variability but are chronic in nature. We cannot entirely discount the possibility of a longer-term evolution towards eutrophy whether by persistent and substantially increased phytoplankton or changes elsewhere in the food-web. However, the modelling indicates that winter-time light limitation acts as a 'bottleneck', which combined with relatively rapid flushing and benthic denitrification make it unlikely that the system will undergo extreme changes in response to the levels of farming presently permitted in this system.

The Board of Inquiry which approved the new Ngamahau salmon farm imposed numerous consent conditions. Amongst these was a ruling that the Sounds water quality should not be allowed to move significantly towards a eutrophic state. In that context, eutrophy was defined to be chlorophyll concentrations that were persistently (annual average) above 5 mg chl m^{-3} over a large area. The model indicates that this threshold will not be exceeded even under our worst-case scenario (*approved farms, no denitrification*).

Whilst we believe that the inferences that we draw from our modelling are robust, we caution that almost no sensitivity trials have been undertaken to justify that belief. We therefore recommend that further sensitivity trials be undertaken to determine the degree to which the model predictions are robust against assumptions regarding:

- Sinking speed of fish and mussel faeces (introduce a third detrital class specifically for these very fast sinking materials)
- Light attenuation (what happens if we take better account of the differential attenuation of different wavelengths, and topographic shading?)
- Formulation of the zooplankton mortality term
- Our decision to assume that real-world dissolved organic nitrogen is biologically inert
- Sensitivity to Cook Strait boundary conditions

We described the deposition footprints of the five fish farms in Tory Channel/Queen Charlotte (namely: Te Pangu, Clay Point, Ngamahau, Ruakaka & Otanerau) using a particle-tracking model driven by the 3D hydrodynamic simulations on a 100 m horizontal resolution grid. The model predicted that farm-derived particulates settle to the seabed rapidly (within minutes). Thus, dispersal of the farm-derived waste is driven by tidal currents rather than longer-term residual flow patterns.

Tidal speeds are higher around the three farms in Tory Channel (Clay Point, Te Pangu and Ngamahau) than around Ruakaka or Otanerau. Thus, the benthic footprints of the latter two farms are less extensive. At present, there are no direct measurements of deposition rates at any of these farms, but the predicted rates at the pen perimeter are similar to those that have been measured at Waihinau.

The predicted rates of deposition are similar to those which have been predicted by the Cawthron Institute using an entirely independent model (DEPOMOD). To a first approximation, the spatial patterns are also similar, but it is noteworthy that our deposition footprints around Te Pangu and Clay Point farms are crescent-shaped whereas the DEPOMOD ones are more nearly elliptical. By visual comparison (only), we believe that our crescent-shaped footprints better reproduce the measured shapes of the benthic environmental footprints (inferred from measurements of the composition and abundance of the benthic fauna) at these sites. We believe that the differences stem from the fact that our modelling includes the effects of horizontal variations in flow whereas DEPOMOD assumes that the current field is spatially uniform in the horizontal. In this instance, we do not believe that the discrepancies between the predictions of the two models are sufficiently large to raise any concerns. Nonetheless, we believe that the discrepancies provide some evidence that DEPOMOD (in its present release variant) is not the most suitable tool for predicting benthic deposition when farms are situated in locations where eddy activity will be significant (i.e. close to headlands which interrupt tidal currents).