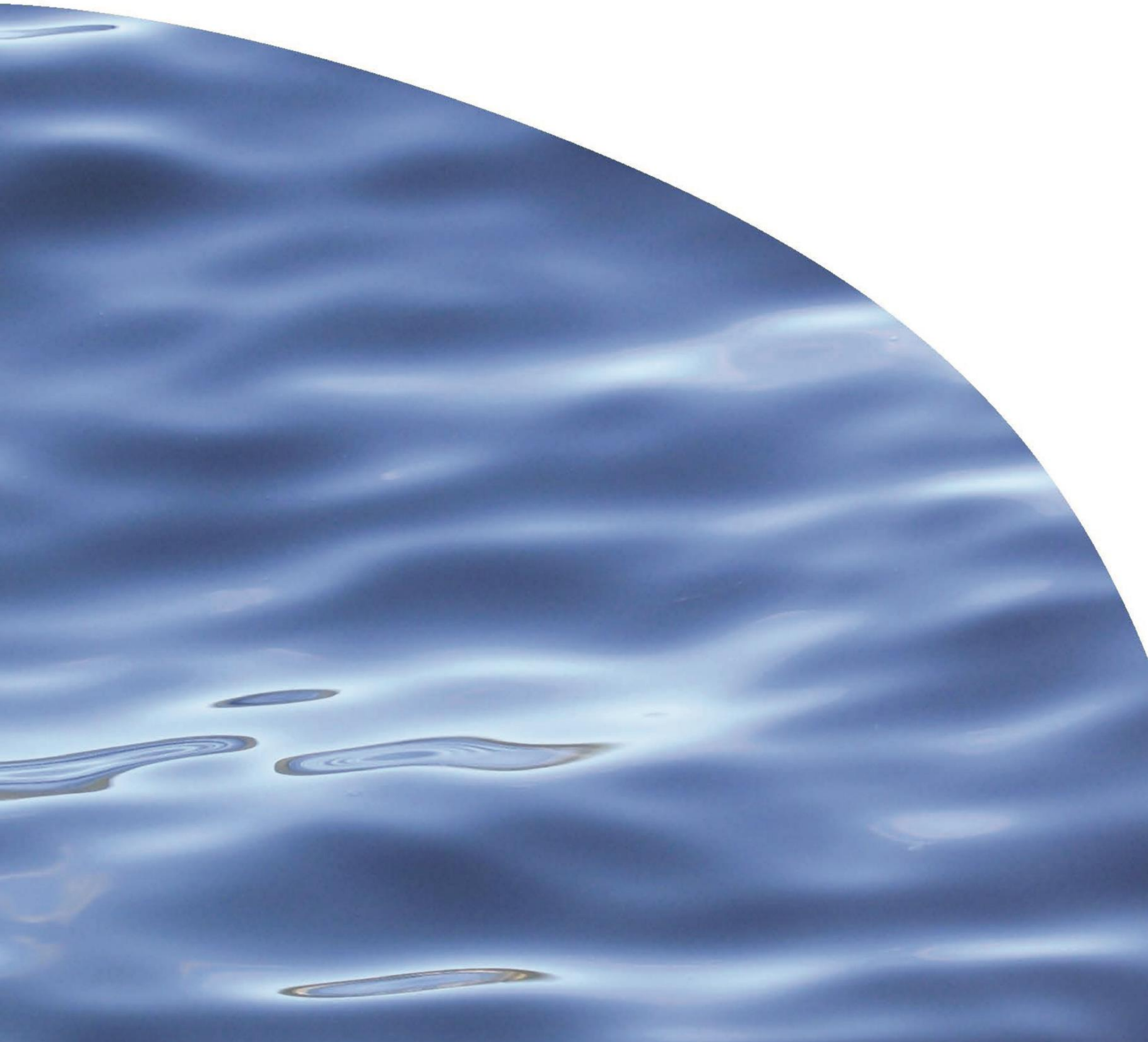
CAWTHRON
The power of science®

REPORT NO. 2923

PEER REVIEW OF THE MARLBOROUGH SOUNDS BIOPHYSICAL MODEL PREDICTIONS



PEER REVIEW OF THE MARLBOROUGH SOUNDS BIOPHYSICAL MODEL PREDICTIONS

BENJAMIN KNIGHT

Prepared for Ministry for Primary Industries

CAWTHRON INSTITUTE
98 Halifax Street East, Nelson 7010 | Private Bag 2, Nelson 7042 | New Zealand
Ph. +64 3 548 2319 | Fax. +64 3 546 9464
www.cawthron.org.nz

REVIEWED BY:
Don Morrisey

APPROVED FOR RELEASE BY:
Chris Cornelisen

ISSUE DATE:13 September 2016

RECOMMENDED CITATION: Knight B 2014. Peer review of the Marlborough Sounds Biophysical Model Predictions. Prepared for Ministry for Primary Industries. Cawthron Report No. 2923. 19 p.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. BACKGROUND & SCOPE

The Ministry for Primary Industries (MPI) has requested Cawthron Institute to undertake a review of the water quality models (hereafter referred to as 'the models') produced by the National Institute of Water and Atmospheric Research (NIWA) for the Marlborough Sounds region. Background on these models and their construction can be found in Hadfield et al. (2014) and Broekhuizen et al. (2015).

This report provides a high level assessment of the suitability, benefits and limitations of the models, and provides comment on their ability to predict potential changes in the distribution and form of nitrogen under future finfish farming scenarios provided in Broekhuizen and Hadfield (2015) and Broekhuizen and Hadfield (2016a, 2016b). It is important to note that this review is not intended to provide a detailed assessment of the results of the modelling.

This review also builds on the initial validation work undertaken by Hadfield et al. (2014) and Broekhuizen et al. (2015). I have previously reviewed Hadfield et al.'s (2014) Queen Charlotte Sound (QCS) model. Although I noted that some uncertainty in the transport characteristics in Tory Channel was possible, I concluded that the model performance more than meets basic requirements for use in resource management planning discussions (Knight 2014). A short review of the Pelorus Sound model was also undertaken by MetOcean Solutions Limited (B. Beamsley, MetOcean Solutions Limited, pers. comm.) before the model was finalised in Broekhuizen et al. (2015). This review does not attempt to repeat the previous assessments, but rather focuses on the ability of the models to simulate finfish farming scenarios.

This report is structured as follows: Section 2 provides a summary of my earlier review of the Queen Charlotte Sound biophysical model developed by Hadfield et al. (2014), Section 3 provides background to the modelled future scenarios, and Section 4 provides a review on the ability of the models to predict potential changes to the water column environment.

2. SUMMARY OF THE EARLIER QUEEN CHARLOTTE SOUND MODEL REVIEW

My previous review of Hadfield et al.'s (2014) Queen Charlotte Sound (QCS) biophysical model looked at its construction and compared the modelled outputs with measurements undertaken by the Marlborough District Council in 2013 (Knight 2014). I generally agreed with the main concluding statements presented in Hadfield et al.; i.e., that mussel farm effects in the region will be small relative to natural variability, and that finfish farm effects in the region will be widespread and generally smaller than natural variability, except close to the farms. However, it was also noted that simplifications and uncertainties in the model could result in under- or over-estimates of changes to the abundance, distribution and forms of nitrogen in the water column.

2.1. Limitations

The previous assessment described the following limitations of the QCS model:

- restriction of spatial resolution to 200 m grids for the main model runs
- a simplified chemical regime was used with only nitrogen tracked within the model
- simplified detrital classes were used
- simplified phytoplankton ecology was used with only a single class modelled
- simplification of phytoplankton physiology was used, with half-rate constants used to model uptake processes
- simplified zooplankton ecology was used with only a single class modelled
- higher trophic processes were excluded, with dampening of zooplankton undertaken through fixed mortality of zooplankton.

Despite these limitations, the design choices undertaken were appropriate for the purposes of gauging possible system-wide ecological effects on phytoplankton. Ultimately modelling of complex marine systems requires trade-offs, which result in some limitations. For instance, the choice to model nitrogen only and to use simplified ecological variables were necessary to ensure that computational requirements were feasible.

Design choices will also limit the use of the model for some applications. For example, although the wider system dynamics may be captured by the model, the spatial resolution may limit the accuracy of the model within embayments. Nesting of higher resolution models may be required to answer questions at these scales.

2.2. Conclusions

The previous review considered that the models would be sufficient for the Marlborough District Council to use in combination with existing data, expert knowledge and other tools (e.g. targeted *in situ* research) to address a wide range of resource-management questions, such as:

- siting of monitoring locations for assessing system-wide changes in the state of the environment
- formulating consent conditions (e.g. monitoring locations)
- assessing the potential threshold effects (i.e. whether new pressures are predicted to trigger large environmental changes)
- considering the trophic state sensitivity to nutrient changes for broad regions.

The value of the model lies in its ability to identify the response of the system to changes in forcing factors (*e.g.* nutrient input changes). While I could not comment on this ability of the model based on the evidence presented in Broekhuizen et al. (2014), comparisons with the results of experimental studies may be helpful in validating the model's predictions. For example, nutrient manipulation experiments using mesocosms undertaken by Carter (2004) in Pelorus Sound in the early 2000s, showed quite large responses by phytoplankton populations to additions of nitrogen. I discuss this further in the review of the modelled scenarios (see Section 3.2).

3. REVIEW OF MODELLED SCENARIOS

3.1. Feed input scenarios

Model predictions in Broekhuizen & Hadfield (2015, 2016a, 2016b) are based on a large number of scenarios across a range of feed inputs. To simplify the current model review, my assessment is based on the following four scenarios of feed input which are considered relevant to finfish aquaculture in the Sounds:

1. an existing 'worst case' scenario, representing a feed loading scenario which is likely to have occurred in the past and for which measurements of N concentrations should be available
2. an existing consented feed scenario, which although may not be realised at present, may be achieved in the future (equivalent to Scenario 1 in Broekhuizen & Hadfield 2016a, 2016b)
3. a proposed 'first-stage' feed input scenario, against which any predicted model changes could be validated during farm development
4. a future predicted sustainable feed level (PSFL) scenario in which all new areas are able to operate at the feed-input that is consistent with maximum best management limits for impacts on the seabed beneath the farms.

The existing feed scenario (Scenario 2, above) considers an estimated current feed loading based on information available for the New Zealand King Salmon Board of Inquiry[1], particularly from tables prepared for my own evidence[2], and the 'probable sustainable' feed levels presented in the evidence of Keeley[3]. Note that variations from year-to-year are possible, so this estimate may need to be refined.

Both of the future scenarios (3 and 4 in the list above) assume that the poorly performing existing sites are retired to make way for better-located sites. The proposed 'first-stage' scenario is not directly related to the scenarios in the modelling reports, but has been proposed as a focus for stakeholder discussions (pers. comm. Rebecca Clarkson, Aquaculture Direct). I consider this an important scenario for consideration as it enables initial checks to be made on the model to assess its performance. It is my understanding that the first stage of development is suggested to be 50% of the PSFL scenario and would be staged over a period of 5 to 10 years. Therefore, time would be available to collect new data and test the response of the existing models.

[1] The New Zealand King Salmon Board of Inquiry considered the proposal from The New Zealand King Salmon Co. Limited (NZ King Salmon) for two plan change requests to the Marlborough Sounds Resource Management Plan (MSRMP) and applications for resource consents for salmon farms and salmon farming at nine sites in the Marlborough Sounds. See http://www.epa.govt.nz/Resource-management/previous/king-salmon/Pages/default.aspx for additional details.

[2] Benjamin Knight - Supplementary Document of Figures and Tables (pdf, 1.34mb)

[3] Nigel Keeley - Supplementary Document of Tables (pdf, 189kb)

The PSFL scenario is also lower in its total feed loading than most scenarios presented in the reports of Broekhuizen and Hadfield (2016a, 2016b), and considers likely sustainable feed loadings based on the outcome of recent benthic (seabed) modelling. Benthic modelling has had a long history of validation in the Marlborough Sounds; a scenario based on the benthic modelling limits is realistic for the purposes of this review[4].

3.1.1. Queen Charlotte Sound

In QCS, the proposed 'first-stage' feed input to the new farms (Table 1) represents an 8% reduction of relative to feed loadings for existing farms in the region (compare the totals for columns 3 and 4). When the consented load for the existing farms is compared with that for the proposed new farms, there is a reduction of 3% in feed input (compare totals for columns 5 and 6). However, when the PSFL scenario for the new farms is compared with the existing level of feed inputs, there would be almost a doubling over the current level of feed inputs (compare columns 3 and 6). It is the effect of this last increase for which accurate water quality model predictions will be particularly valuable. Previous model validation for existing feed levels assessed in Knight (2014) considered a comparison to MDC collected data. However, the new scenarios require the model to extrapolate well beyond the existing feed levels.

Table 1. Comparison of existing and proposed annual feed inputs for Queen Charlotte Sound. Feed inputs given in tonnes per year. PSFL = predicted sustainable feed levels.

1. New/Old	2. Location	3. Existing	4. Proposed First Stage	5. Existing (Consented)	6. PSFL
New	Tipi Bay*		750		1,000
New	Motukina*		750		1,000
New	Te Weka		1,000		1,800
New	Tio Point		1,000		1,600
Old	Clay Point	3,500	3,500	6,000	6,000
Old	Te Pangu	4,000	4,000	5,000	5,000
Old	Ruakaka	2,000		3,000	
Old	Otanerau	2,000		3,000	
Old	Ngamahau	500		4,000	4,000
	Totals	**12,000**	**11,000**	**21,000**	**20,400**

[4] The highest levels of benthic models that have been validated to date in the Marlborough Sounds consider feed levels of less than 5,000 tonnes/year. Therefore, I consider that there may also be some uncertainty in high (> 5,000 tonnes/year) feed loading scenarios for the benthic models.

3.1.2. Pelorus Sound

In contrast to the proposed QCS examples, a three-times increase in total feed inputs for Pelorus Sound is proposed for the first stage of development (Table 2). Although this is a large relative increase in the amount of feed, it should be noted that the magnitude of the proposed Pelorus Sound increases are comparable to the existing level of feed inputs into QCS.

Table 2. Comparison of existing and proposed consented annual feed inputs for Pelorus Sound. Feed inputs given in tonnes per year. PSFL = predicted sustainable feed levels.

New/ Old	Location	Existing	Proposed First Stage	Existing (Consented)	PSFL
New	Horseshoe Bay		750		1,500
New	Richmond South		2,500		5,000
New	Mid-Channel Waitata		3,500		7,000
New	Blowhole North		2,000		4,000
New	Blowhole South		2,500		5,000
Old	Forsyth	2,000		3,000	
Old	Waihinau			3,000	
Old	Crail Bay (combined)	1,000		3,000	
Old	Beatrix[1]	500		1,000	1,200
	Totals	**3,500**	**11,250**	**10,000**	**23,700**

[1.] Estimated existing and consented amounts

Direct comparison to an existing system was not undertaken in Broekhuizen and Hadfield 2016b, which suggests that the water quality model will be somewhat stretched beyond the conditions for which it has been calibrated. This may not be an issue because the environment already experiences large natural variation in N concentration and the proposed feed N inputs are likely to be small compared to natural variation (e.g. Zeldis et al. 2008, 2013; and my own estimates of oceanic inputs for the Board of Inquiry).

The proposed long-term increase in annual feed inputs for Pelorus Sound (up to 23,700 tonnes of feed) represents almost a seven-fold increase on the existing level of input (3,500 tonnes). The modelling report also presented scenarios with even higher rates of feed input (up to 31,000 tonnes in Pelorus Sound: Scenario 8 of Broekhuizen and Hadfield 2016b). This suggests that the models are being stretched to a large degree and therefore a discussion of potential supporting evidence is relevant.

In short, based on this initial assessment, it appears that the models for both sounds are being used to predict responses to substantial feed increases far beyond the levels for which they were validated (i.e. the existing feed levels). On the basis of this assessment it seems that there would need to be a higher standard of proof on the accuracy of the models if they are the sole method of estimating effects.

3.2. Predicted magnitudes of effects

It was apparent from the models that even at high levels of feed, the total nitrogen (TN) responses (e.g. sum of chemical + phytoplankton + zooplankton responses) across both QCS and Pelorus Sound were small (i.e. < 3% increase beyond 'baseline' scenarios). In the case of Pelorus, maximum changes of chlorophyll-*a* of less than 5% are also predicted to occur (Broekhuizen & Hadfield 2016b), with changes of up to 8% predicted for Grove Arm in QCS, although a scenario with Tio Point was not included in the QCS report (Broekhuizen & Hadfield 2016a).

A limitation of these results is that the modelled changes relate to 'existing' maximum *consented* feed inputs. *Actual* current feed inputs are less than maximum consented inputs. In the comparison of feed inputs (Table 1 and Table 2), some of the differences in feed inputs between the existing and consented changes are quite large. Consequently, I would expect a larger biological change (e.g. in concentrations of chlorophyll-*a*) associated with a comparison to the actual current feed input. Given that the report is trying to predict potential changes resulting from altered farm locations, it seems that a comparison to the existing environment would be more relevant[5].

There is a graph in the Pelorus model report (Figure 3-2 in Broekhuizen & Hadfield 2016b) that shows an approximately linear Sound-wide response of TN concentration to increases in feed loading. Assuming that the linear response holds true for lower inputs, this can be used to provide a simple estimate of TN changes for the feed inputs for the proposed new farms relative to actual existing feed inputs or current maximum consented inputs. In the case of Pelorus Sound (Table 3), this results in a slightly larger increase in the modelled effect of the new farms on concentration of TN from about 1.63% relative to the current consented input to about 2.25% relative to the current actual input. If the more realistic PSFL scenario is considered (e.g. those consistent with acceptable benthic effects), the modelled TN changes are smaller, at an estimated 1.13% in Pelorus Sound (Table 3).

[5] Note that this would not be the case if the existing sites had the potential to grow to their maximum consented feed levels. However the long history of these sites suggests that they would be unlikely to achieve their consented maxima without significant technological advances, so I consider the existing levels of feed to be more appropriate scenario for comparison.

Table 3. Estimated relative increases in Pelorus Sound for probable benthic and maximum scenarios when compared to existing ('baseline') scenarios. Note that the existing scenario assumes a linear response from the slope (0.00244 mmol N/m^3/t feed/day) presented in Broekhuizen and Hadfield (2016b) and an estimate of the intercept calculated for this review (7.095 mmol N/m^3). 'Benthic PSFL' refers to the predicted sustainable feed level consistent with acceptable benthic effects. 'n.a.' = not applicable.

Scenario	**Broekhuizen & Hadfield 2016b scenario**	**Feed rate (t/day)**	**TN conc. estimate**	**Increase relative to:**	
				Baseline consented	**Baseline actual**
Baseline (consented)	1	43	7.20		
Baseline (actual)	n.a.	25	7.16		
New farms maximum	8	91	7.32	1.67%	2.23%
Benthic PSFL	n.a.	58	7.24	0.51%	1.13%

However, this analysis relies on Figure 3-2 in Broekhuizen & Hadfield 2016b, which appears to be inconsistent with the Table 1-1 in Broekhuizen & Hadfield 2016b that shows annual feed loadings. For example, scenario one in Table 1-1 notes an annual feed loading of 12,275 tonne of feed whereas a daily feed rate of 43 tonnes is presented in Figure 3-2, which is equivalent to an annual feed rate of 15,330 tonnes. I have queried this inconsistency, which appears to be related to a possible timing differences in the feed records presented in Table 1-1 and the modelled feed loads (Figure 3-2) (pers. comm. Broekhuizen). Similarly, cumulative rounding errors in the incorporation of feed into the model may also create a difference. Assuming Figure 3-2 accurately reported rates used in the model, this does not affect the conclusions presented here, but clarification will be required in Broekhuizen and Hadfield (2016b)[6].

It is worthwhile comparing small modelled changes, to measured changes from field-based experiments. For example, up to an eight-fold increase in chlorophyll-*a* over four days was noted by Carter (2004) for some of the months (Figure 1).

[6] Also note that a typographic error also appears in the executive summary, which states that the "TN concentration is predicted to rise by approximately 0.025 mmol N m^{-3}.", rather than 0.0025 mmol N m^{-3} which is the correct number.

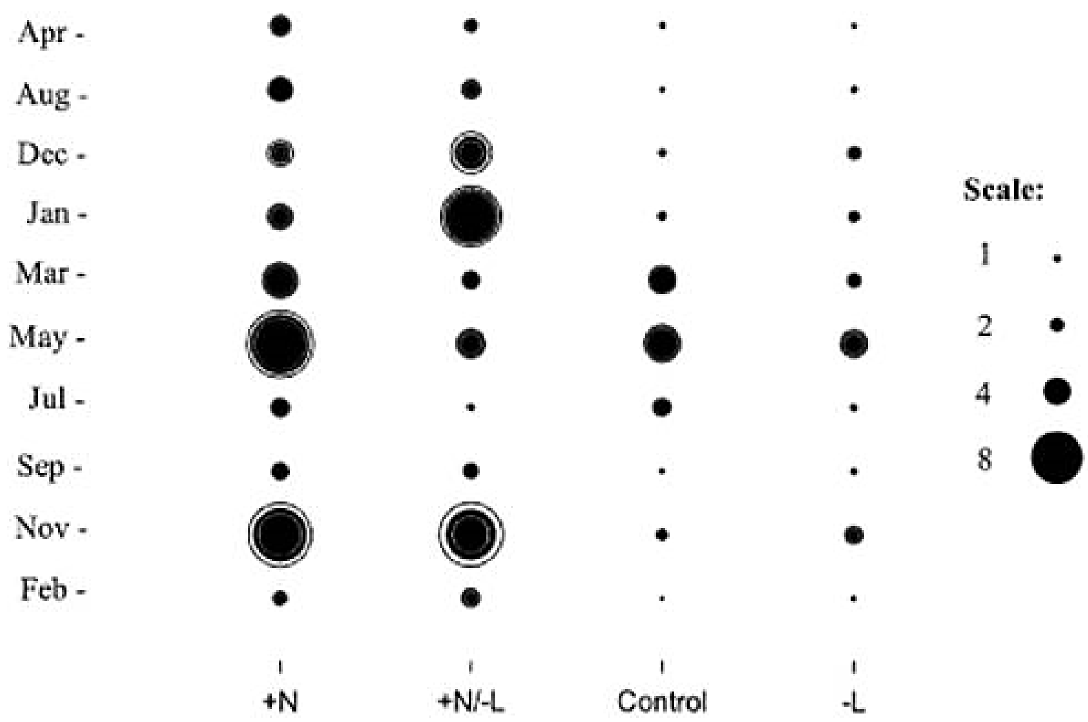


Figure 1. Proportional change in chlorophyll-*a* over four days from nitrate addition experiments in Beatrix Bay, Pelorus Sound (from Carter 2004). Mean is shown as a black circle. Standard error is shown as a grey ring. +N refers to nitrate addition, +N/-L refers to nitrate addition with reduced light and –L refers to a reduced light environment only (i.e. no additional nitrate).

I have not undertaken a detailed assessment of Carter's (2004) results for this or the previous review, but presumably the following factors would need to be considered when drawing comparisons to model predictions:

- The experiments of Carter (2004) do not allow for dilution (as would occur in a real system).
- How do the nitrate additions compare to a salmon farm scenario: were the additions higher or lower?
- The presentation of relative changes can be misleading if very low concentrations were present: what where the absolute changes in chlorophyll-*a* concentrations?

Although there may be limitations to this work, the results at least provide some empirical evidence for model predictions.

3.3. Additional information requirements

Unlike the previous reports that provided additional validation information, less information on the model functioning is provided in the latest reports of Broekhuizen and Hadfield (2016a, 2016b). I consider that relevant information should include information on nitrogen fluxes, such as:

1. denitrification losses (i.e. direct losses of N to N_2 from the models)
2. flushing losses of nitrogen (i.e. how much N is lost to Cook Strait?)
3. estimated waste nitrogen inputs (rather than feed inputs).

This additional information is very useful for reviewing purposes, but unfortunately is not currently available. In order to provide additional information that may help with a general understanding of the importance of these data, I elaborate on this requested information here.

3.3.1. Denitrification losses

Denitrification refers to a process whereby conversion of N to its gaseous form (N_2) by bacteria results in direct losses of N from real world environments. With the exception of the harvesting of mussels which can physically remove some nitrogen from the Marlborough systems, denitrification is a major pathway for the loss of nitrogen from the model domains. I therefore consider it important information to understand in a modelling context.

In my earlier review, I assumed that the denitrification rates used were appropriate, despite a very simple formula being employed. This simple formula used a default model formulation that assumes that a 75% loss of detrital nitrogen occurs when solid forms of N (e.g. from detritus or salmon faeces) contact the seabed, with the remaining 25% converted to inorganic nitrogen in the bottom water cell of the model. This means, for example, that 75% of the detrital nitrogen within fish faeces will instantly be lost from the model.

Waste N from finfish is mainly in dissolved forms (representing ~60% of input N) rather than in fish faeces (~15% of input N). The remaining ~25% of the nitrogen is assumed to be retained within the fishes' bodies and is removed at harvest. Modelling the loss of N from fish faeces by denitrification assumes a linear increase in denitrification with increasing feed. However this might not be the case and therefore checking that the modelled rate of denitrification is appropriate will become increasingly important under the high feed scenarios considered here.

Given that an increase in the production of faeces would be expected under higher feeding loads, I would expect the modelled rate of denitrification to be higher in the updated scenarios. Some increase in a real system would also be likely given the results of Kaspar et al. (1985), who showed that moderate organic enrichment can help to fuel increased denitrification rates. They also found that, at very high levels of enrichment, denitrification could also be reduced. This empirical evidence suggests that the linear relationship for denitrification assumed by the model may not hold for all scenarios. However, without access to a comparable scenario in which denitrification is switched off, I cannot assess what the areal rates of denitrification are and cannot determine if they are realistic.

3.3.2. Flushing losses of nitrogen

In addition to denitrification and harvesting of stock, which remove nitrogen from within the model, the other process by which nitrogen may be removed from the model is if it passes outside of the modelled area ('domain'). The edges of the model domain, where water movement cannot be tracked, are called 'open boundaries'. There are several ways of specifying conditions at the boundaries. The simplest approach is to fix concentrations of N at the boundary based on set values (hopefully based on real measurements near to the boundary). More complex arrangements can 'remember' the properties of the water that has flowed past it and use it to affect the incoming concentrations at a later time.

A simple situation is where tidally-forced water exits a model domain and can then come back into the model. For example, if the concentrations leaving the model were higher than the pre-set incoming 'oceanic' concentrations, the boundaries provide an avenue for losing N from the model. Similarly, if the pre-set 'oceanic' N concentrations at the boundaries are higher, then N could be gained. A relevant example is where a model element at the boundary is a source of N (e.g. a salmon farm). In this situation, assuming perfect tidal symmetry over a tidal period, only half of the added N from the farm would be incorporated into the model (i.e. 50% of the N would be lost). Consequently, this mechanism is very important to understanding the flow of nutrients under scenarios of elevated N input within the sounds.

For both the Pelorus and Queen Charlotte models, the model boundaries are located some way from the entrances of each sound. Nevertheless, it is clear that farms located near to the entrances would be expected to lose a larger proportion of their nutrient to Cook Strait than farms located within the sounds. This information was not directly available for this review, but it would be useful to help describe the importance of physical mechanisms, which can drive losses and gains in N to the region.

3.3.3. Waste nitrogen inputs

As was the case in my earlier review of the QCS model, I am unable to confirm the conversion of feed to N and consequently the loads of N that enter the model domain. Consequently, I have had to derive my own estimates of N loads using the simple approach I applied in the Board of Inquiry process. However, it should be noted that a relatively complex model was used to predict salmon-farm stocking in the model scenarios. The salmon farm models used are able to track both the age class progression of stock and the relevant feeds that are provided to them (Table 4).

Table 4. Examples of simple estimates of dissolved inorganic nitrogen (DIN) and total nitrogen (TN) loss from a salmon farm under high and low protein feed scenarios and an assumed feed conversion ratio (FCR) of 1.7. These estimates use a modified approach to that presented in Gowen & Bradbury (1987). This approach could be updated with locally relevant data if retained fish nitrogen content (Fish N) and other information is available.

Description	High Protein Feed	Low Protein Feed
FCR	1.7	1.7
Feed (Tonne/yr)	1000	1000
Percentage protein in feed	45%	35%
Percentage N in protein (16% - Stead and Laird 2002)	16%	16%
Fish N (27.2 kg retained/tonne of fish - Bromley and Smart 1981)	27.20	27.20
Faeces production (26% - Butz & Vens-Cappell 1982)	26%	26%
N % in faeces (4% - Penczak et al. 1982)	4%	4%
Feed N (kg/tonne of feed)	72	56
Feed N (kg/tonne of fish produced)	122.40	95.20
Faeces production (kg/tonne fish)	442	442
Annual Estimates		
Annual DIN loss (kg per tonne of feed per annum)	**45.60**	**29.60**
Annual TN loss (kg per tonne of feed per annum)	**56.00**	**40.00**

The calculation for directly estimating the loss of N to the environment, summarised in Table 4, is simply:

Total waste nutrient = Input feed nutrient– Nutrient retained by fish

Based on my calculations, about four times more dissolved N would be expected to be released than N in the faeces. However this can vary depending on many factors, such as feed type, digestibility etc. Existing N inputs from the modelled fish farms have not been provided for this review, so it is not possible to directly compare the simple estimates above with the N inputs for the scenarios that have been modelled. However, the report authors have agreed to provide this information in future, so it will be possible to confirm this at a later date.

3.4. Estimates of N fluxes

Assuming the modelled inputs are comparable to my own N input estimates (presented in Table 4) and using published information on the volume of water

(1.07 × 10^{10} m^3; Broekhuizen & Hadfield 2016b) and mean TN concentrations in Pelorus Sound (Figure 2), it is possible to estimate the rates of total loss for Pelorus Sound. This information is presented below to help estimate N losses in the model.

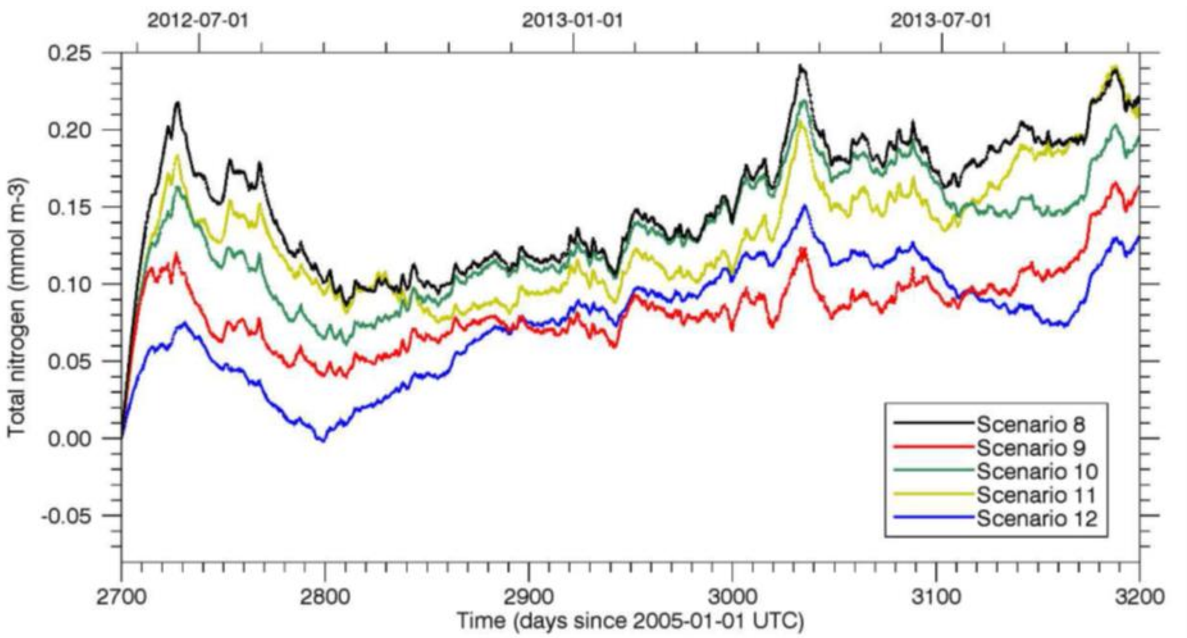


Figure 2. Time-series of the difference between the volume-averaged concentrations of total nitrogen (alternative scenario minus baseline scenario). The graph illustrates the concentration differences between scenarios 8 to 12 of Broekhuizen and Hadfield (2015), with scenario 8 having the highest feed loading (31,080 tonnes/yr) of any scenario. Total nitrogen is calculated as the sum of nitrate, ammonium, detrital, phytoplankton and zooplankton nitrogen. Simulation time is expressed days-from 1 January 2012. Figure from Broekhuizen and Hadfield (2015) with caption text altered for this review.

As noted previously, exact N inputs have not been provided. Therefore, I assumed that the N released is the average of a low and high protein diet and that 75% of the solid N load is instantly removed through the denitrification scheme applied in the models (i.e. 25% of the solid load, ~2.6 kg N/t feed, is added to the dissolved load). From this I estimated that the average dissolved N release will be about 40 kg N for every tonne of feed[7]. The scenario with the highest feed input (scenario 8) would be expected to release about 1,240 tonnes of N[8] per year. The baseline considers a feed input of 12,271 tonnes per year which equates to an N input of about 491 tonnes of N[9] per year. Consequently, the simulated increase in scenario 8 is 749 tonnes of N per year[10].

[7] (45.6+29.6)/2 = 37.6 kg N/t feed + 2.6 kg N/t feed is about 40 kgN/t feed
[8] 31,000 feed/year x 40 kg N/t feed = 1,240,000 kg N/year
[9] 12,271 feed/year x 40 kg N/t feed = 491,000 kg N/year
[10] 1,240 - 491 = 749 tonne of N per year

Under scenario 8, in the first 50 days of the model run, an increase in TN concentration of about 0.23 mmol/m^3 (3.22 mg N/m^3)[11] is recorded. This equates to a TN load increase of about 34.5 tonnes N[12] out of an estimated additional N input of about 103 tonnes over the same period[13]. Over 50 days that equates to about 30% of the estimated N load released from the new farms being retained within Pelorus Sound.

These calculated retention rates could be recalculated over different periods of the model run. However given that similar concentrations are observed after a longer period, clearly the proportion of retained N must decrease further. For example, after 250 days it appears the concentrations are similar, so the mean retention rate would be only one fifth of the initial rate (i.e. 6%).

It is difficult to assess the accuracy of these numbers, but given my early example of a farm located at the boundary having 50% retention of nutrients, the initial result seems plausible given that additional loss of N from denitrification could also occur. Over time, as N concentration within the sound increases, it would eventually become higher than the water outside of it, and consequently the ocean outside of the sound would become a sink for additional nutrients.

However, it is important to note that the biological model employed in the scenarios reviewed here cannot fully account for the actual complexities of the real systems. For instance, it is clear that the Marlborough Sounds are naturally more enriched than the oceanic waters outside of them. Consequently the possibility that these systems act as ‘biological pumps’ to pump and retain nutrients in the Sounds should not be discounted. The biological mechanisms which can facilitate this, particularly in estuarine systems like the Pelorus Sound, can include vertical migration of plankton, a factor that is not included in these models.

Consequently while the model results may be plausible, I note that caution in their application is required, particularly if high feed loading scenarios are considered. Given the large amount of missing information I cannot state a personal level of confidence in this assessment. That would need, at a minimum, clarification of the N inputs associated with in the model.

3.5. Model response to new nitrogen inputs

As I noted in my previous review (Knight 2014), which had some additional N flux information, it was still difficult to assess whether the small biological responses presented in the model reports are accurate.

[11] Note uses a molar mass of 14g/mol of N
[12] 3.22 mg N/m^3 x 1.07 x 10^7 m^3 / 10^9 = 34.454000 t N
[13] 749 tonne of N per year x 50 days/365 days = 102.6 tonne of N

Given that the models are being asked to predict increases in finfish derived N inputs that represent almost a 1000% increase on existing inputs in some scenarios, it is my opinion that the model predictions should be considered alongside other forms of evidence.

Some examples of other evidence that may corroborate predictions from modelling would be:

1. Consideration of the present level of environmental response to estimated changes in N loading. For example, can the research of Zeldis et al. (2008, 2013) give us insights into the existing response to natural changes in N inputs and how do these compare to the scenarios modelled?
2. Estimation of the response of the water column to nutrients by taking water samples and adding nutrients to them, for example, the mesocosm results of Carter (2004).
3. Comparison with a similar system that already contains a higher level of finfish feed and that has been well monitored. For example, can present day QCS results be used to estimate effects of feeding increases on Pelorus Sound?

4. GENERAL DISCUSSION AND RECOMMENDATIONS

The aim of this review has been to provide a high-level assessment of the benefits and limitations of the model predictions in assessing effects of potential future feed scenarios.

The existing models appear to be well-constructed and the communication of results is clear. The present modelling results suggest that sound-wide changes in both sounds will be small (< 5% change in TN). Although I have raised several concerns in my review, the clear benefit of the modelling system is that it has the potential to simulate the systems in a physically and biologically realistic manner. Specifically it is the only method available that can consider the spatial effects both for nutrient inputs and exports and is hence important component in an effects assessment process.

The models presented here are used to assess effects of higher feed inputs (i.e. the current consented maximum) than currently exist in the regions. Consequently, if the proposed scenarios were to be realised, I consider the models would currently underestimate effects in the region, particularly in Pelorus Sound. Given the information available to me, and assuming a linear response of N release to feed input, it appears that modelled changes in Pelorus Sound of less than 3% are possible for the highest feed-loading scenario (ca. 31,000 tonnes/year) when compared to an existing scenario. However, this level of feed input would probably cause exceedance of limits on effects on the seabed. Based on these benthic limits, it appears that the Pelorus scenario is probably an overestimate of the benthic carrying capacity of the sites. Assuming that initial benthic modelling is accurate, a limit closer to 20,000 tonnes/year is more realistic. This would be associated with modelled sound-wide changes in TN of less than 2%. Consequently it appears that the differences in the selected baseline will not have a large effect on the conclusions presented in the report.

The limited availability of information has made it difficult to assess the accuracy of the modelled small biotic responses to feed increases. Consequently, I have not been able to determine the accuracy of the models. From my perspective, the models contain a lot of unknown processes at present. Additional information will require further efforts to extract and process, but it should be easier to understand the processes that lead to the presented results in future.

Although the modelled responses are small, I consider that accuracy of the models needs to be considered in more detail when used with scenarios of large increases in feed input. A cursory review of results presented by Carter (2004) shows empirical evidence that the chlorophyll-*a* response to additional N can at times be high. There are many questions that would need to be considered before determining the relevance or otherwise of Carter's results. The sensitivity of phytoplankton to additional nutrients is at the core of the model results. In my opinion, the models are being stretched beyond their original scope and purpose, particularly in the Pelorus Sound. If the models are to be used as the sole source of assessment, they will require a high level of confidence.

This level of confidence may be difficult to achieve in the short-term; the following two sources of information may help corroborate, or challenge, the model results:

1. information from experimental studies (e.g. Carter 2004), or
2. information from natural variations in nutrient concentrations at the spatial scale of the Sounds (e.g. Zeldis et al. 2008, 2013).

Despite my concerns and recognition of many unknowns, I nevertheless consider that the model results are plausible. This is based on both the experience of the researchers, the quality of the modelling tools, and my own modelling work which considered similar levels of proposed feed increase.

My personal opinion is that the proposed first-stage changes in feeding are likely to produce small water-quality changes in QCS. However, it is difficult to assess what potential changes could occur in the region under the higher feed loading scenarios. Regular harmful algal blooms occur in the QCS region (e.g. MacKenzie et al. 2011, 2012, 2013, 2014), therefore any increase in feeding in the area would need to be carefully monitored. This should also occur alongside appropriate staging and management responses to manage the risk of algal blooms or other undesirable effects.

As I have noted in this review, potentially large initial increases in feed for the farms in Pelorus Sound (and therefore increases in N) have been proposed. The work of Zeldis et al. (2008) suggests that large natural fluctuations in the Pelorus Sound environment have occurred in the past (e.g. 100% changes in particulate N in Beatrix Bay). Although this has resulted in a productive environment for mussel culture, it is not apparent that a highly eutrophic (nutrient rich) environment has resulted from these changes. Natural inter-annual changes in nutrient concentrations are different to persistent inputs that could result from finfish farming; nevertheless information on natural changes may help to place some context around the levels of change that may be expected for different finfish feed scenarios.

The only way to really test the response of the system to new nutrient additions is to increase nutrient loading and measure the response of the real system. In a recent review of the existing state of the environment monitoring by Forrest et al. (in prep), a number of gaps in the present level of monitoring have been identified. These are mainly related to the frequency of measurements in the regions which could prevent 'events' from being observed. Continuous monitoring with instrument buoys and in-water sensors would provide a solution to this problem. If the existing level of monitoring can be increased and any nutrient increases can be phased in slowly over several years, I consider that greater certainty in the modelling responses could be established.

In summary, I consider the model is necessary for the type of assessment being undertaken. However limited availability of information (e.g. the amounts of nitrogen inputs and losses) precludes a comprehensive review of the model. I recommend that predictions of benthic and other types of effects are used initially to focus stakeholder discussions on levels of feed input. These levels would provide more plausible (i.e. lower) feed input scenarios for future water quality modelling. I would also recommend that an expert water quality group be formed to provide and assess additional information that could support or challenge the model predictions. This group may also be able to assist in the implementation of improved monitoring to provide greater confidence that any ecologically important changes in the marine environment is able to be detected and managed appropriately.

5. REFERENCES

Butz I, Vens-Cappell B 1982. In, Report of the FIFAC Workshop on Fish-Farm Effluents., edited by JS Alabaster, EIFAC Tech Paper No. 41, pp. 73-82

Broekhuizen N, Hadfield M, Plew D 2015. A biophysical model for the Marlborough Sounds, Part 2: Pelorus Sound. NIWA Client Report CHC2014-130. 175 p.

Broekhuizen N, Hadfield M 2015. Additional salmon farms in Tory Channel: An assessment of effects on water-quality using a biophysical model. NIWA Client Report HAM2015-039. 95 p.

Broekhuizen N, Hadfield M 2016a. Additional salmon farms in Tory Channel: An assessment of effects on water-quality using a biophysical model (Oyster Bay, Tipi Bay & Motukina Point). NIWA Client Report HAM2016-065, 59 p.

Broekhuizen N, Hadfield M 2016b. Modelled water column effects on potential salmon farm relocation sites in Pelorus Sound. NIWA Client Report HAM2016-012. 88 p.

Bromley PJ, Smart G 1981. The effects of the major food categories on growth, composition and food conversion in rainbow trout (*Salmo gairdneri* Richardson). Aquaculture 23 (1-4): 325-336.

Carter CM 2004. Spatial and temporal dynamics of phytoplankton communities in a coastal ecosystem. Ph. D. University of Canterbury. 177 p.

Forrest B, Knight B, Barter P, Berkett N, Newton M. Opportunities for an Integrated Approach to Marine Environmental Monitoring in the Marlborough Sounds. Prepared for Marlborough District Council. Cawthron Report No. 2924. 42 p. plus appendices (in prep).

Gowen RJ, Bradbury NB 1987. The ecological impact of salmonid farming in coastal waters: a review. Oceanography and Marine Biology 25: 563-575.

Hadfield M, Broekhuizen N, Plew D 2014. A biophysical model for the Marlborough Sounds, Part 1: Queen Charlotte Sound and Tory Channel, NIWA Client Report number CHC2014-116, prepared for Marlborough District Council. 183p.

Kaspar HF, Gillespie PA, Boyer IC, MacKenzie AL 1985. Effects of mussel aquaculture on the nitrogen cycle and benthic communities in Kenepuru Sound, Marlborough Sounds, New Zealand. Marine Biology 85 (2): 127-136.

Knight B 2014. Peer review of the Queen Charlotte Sound Biophysical Model. Prepared for Marlborough District Council. Cawthron Report No. 2586. 18 p. plus appendix.

MacKenzie L, Harwood T, Boundy M, Smith K, Knight B, Jiang W, McNabb P, Selwood A, van Ginkel R, Langi V, Edgar M, Moisan C 2011. An *Alexandrium catenella* bloom and associated saxitoxin contamination of shellfish, Queen

Charlotte Sound, March-June 2011. A report for MAF Food Safety. Cawthron Report No. 1945. 38 p. Available at: http://www.foodsafety.govt.nz/elibrary/industry/psp-bloom-report-final.pdf

MacKenzie L, Harwood T, Watts A, Webber S 2012. *Alexandrium catenella* blooms and associated saxitoxin contamination of shellfish, March-June 2012. A report for the Ministry for Primary Industries-Food Safety. Cawthron Report No. 2182. June 2012. 37pp. Available at: http://www.foodsafety.govt.nz/elibrary/industry/alexandrium-catenella-blooms.pdf

MacKenzie L, Harwood T, Tonks A, Robinson J, Knight B 2013. Seafood safety risks from paralytic shellfish poisoning dinoflagellate blooms in New Zealand; 2012-2013. A report for the Ministry for Primary Industries (MPI) Food Safety. Cawthron Report No. 2346, September 2013. 38 p. Available at: http://www.foodsafety.govt.nz/elibrary/industry/seafood-risks-paralytic-shellfish-blooms.pdf

MacKenzie AL, Knight B, Harwood T 2014. New Zealand paralytic shellfish poisoning update: 2014. A report for the Ministry for Primary Industries (MPI). Cawthron Report No. 2526. 38 p. plus appendices. Available at: http://www.foodsafety.govt.nz/elibrary/industry/new-zealand-paralytic-shellfish-poisoning-update-2014.pdf

Penczak T, Galicka W, Molinski M, Kusto E, Zalewski M 1982. The enrichment of a mesotrophic lake by carbon, phosphorus and nitrogen from the cage aquaculture of rainbow trout, *Salmo gairdneri*. Journal of Applied Ecology 19 (2): 371-393.

Stead SM, Laird LM 2002. Handbook of salmon farming. Springer Praxis, Chichester, UK.

Urlich S 2014 Letter entitled: “Terms of reference for peer-review of Queen Charlotte hydrodynamic model” dated 11 July 2014, 2 p., Marlborough District Council File Ref: E325-001-001

Zeldis JR, Howard-Williams C, Carter CM, Schiel DR 2008. ENSO and riverine control of nutrient loading, phytoplankton biomass and mussel aquaculture yield in Pelorus Sound, New Zealand. Marine Ecology Progress Series 371: 131-142.

Zeldis J, Hadfield M, Booker D 2013. Influence of climate on Pelorus Sound mussel aquaculture yields: predictive models and underlying mechanisms. Aquaculture Environment Interactions 3 (4): 1-15.