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Tauranga Harbour DELWAQ Nutrient Modelling to support the implementation of the National Policy Statement on Freshwater (NPS-FM)

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by
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Cover picture: Seagrass meadows in Matua, March 2022. Photo: Benjamin Stewart.

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Executive Summary

- A DELWAQ nutrient model coupled to a Delft3D hydrodynamic model was set up for Tauranga Harbour and surrounding shelf, and run for three months during summer and three months during winter for 5 years.
- Model results were summarised in 34 different regions, aligned to the BoPRC reporting of sensitive receiving environments in Tauranga Harbour.
- Prior to undertaking the 5-year DELWAQ modelling, a sensitivity analysis was undertaken to tune key modelling parameterisations (primarily sediment denitrification). Nutrient and salinity outputs from the 5-year runs were compared against BoPRC monitoring data to assess performance.
- Salinity was generally over 30 ppt even in winter, except very near freshwater input zones. Flushing time varied substantially across the harbour from less than one day to 9 days.
- Nutrient levels were much higher in the southern basin and increased with proximity to freshwater discharges. Winter nutrient levels were higher for all species, both in terms of background levels, and in areas closer to discharges. This is because of the combined effect of greater freshwater nutrient loading in winter combined with reduced winter algal uptake (groundwater nutrient sources were not included in the modelling).
- The main sources/sinks of dissolved inorganic nitrogen into each region were exchange from surrounding regions, with denitrification becoming important in long-flushing time shallow intertidal regions. Regions into which freshwater discharged directly, were dominated by that discharge. Processes (such as uptake by algae) were more important in summer compared to winter (which contributes to higher dissolved inorganic nitrogen levels in winter). Water travelled quickly in the central region of the harbour, so the central region could be influenced by areas that were quite far away, whereas the small subareas were more influenced by their immediate neighbours.
- Nitrogen loading reductions (modelled as 20% and 40% reductions in concentrations on all freshwater discharges) had most effect on sites that were close to the main discharges (such as Tilby Point, Waikareao and Welcome Bay), whereas areas that were well flushed and near the entrance (Entrance, Kauri Point and Tanners Point), loading reductions had a much smaller effect over the three-month simulation period. Winter loading reductions were greater than summer for nitrate and ammonium, but less than summer for organic nitrogen.
- Only the reductions in areas that were in close proximity to freshwater discharges were large enough to change their classification in terms of susceptibility to macroalgal blooms. However, the large size of the estuary means that it would take a long time (more than 3 months) for changes occurring near regions near sources to mixed into the wider harbour.

- Specifically, for a reduction of 20% in winter, the total nitrogen for 2 sites: 'Wairoa 1' and 'Matahui west' changed from high (class D) to moderate (class C). Site 'Blue Gum Bay' changed from moderate (C) to moderate (B). A further reduction (40%) resulted in 2 sites changing from high (D) to moderate (C): 'Waikareao' and 'Waimapu'. In addition, 'Aongatete'and 'Uretara' changed from moderate (C) to moderate (B). In summer, a reduction of 20% resulted in 4 sites changing from high (D) to moderate (C): 'Wairao 1', 'Wairoa 2', 'Waikareao' and 'Waimapu'. In addition, 'Aongatete' changing from moderate (C) to moderate (B). Further summer reduction did not result in classification changes.
- Areas of greater certainty in the modelling are the flushing times and hydrodynamics. The model was run for multiple years to capture variability in discharge, wind and weather events, and was calibrated by *in situ* measurements.
- Areas of more uncertainty are in the water quality parameterisations such as the various algal uptake rates and parameters controlling denitrification and nitrification, phosphorous transport etc., all of which are highly sensitive to local variations in water properties. Ammonium is particularly sensitive because it transforms quickly to nitrate in the water column. Therefore, the average and seasonal variations of nutrients are in the right range, but the short term (event and tidal scale) variability cannot be easily verified. The modelling does not include groundwater sources or diffuse runoff and small drains directly discharging to Tauranga Harbour.

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1. Introduction

Estuaries are at the receiving end for run-off from catchments, and so in addition to human activities within the estuary itself, they can also be heavily impacted by upstream activities. The NZ National Policy Statement for Freshwater Management 2020 (NPSFM) (NZ Government, 2020) tasks regional authorities to manage land use and activities affecting freshwater for: firstly the health and wellbeing of freshwater bodies and ecosystems (including to manage effects on receiving environments including estuarine systems), secondly the health needs of the people relying on those water bodies, and thirdly the ability of people to provide for their social, economic and cultural wellbeing. In practice, the NPSFM requires establishing freshwater management units (FMUs) for which values and outcomes for those values are defined. The four values which are compulsory for all FMUs are ecosystem health, human contact (the ability to use the water for recreation), protection of threatened species and mahinga kai (the ability to harvest food). In addition, there is a list of other values that may apply depending on the setting and desires of the community and tangata whenua. Once the values are defined, then the next stage is to select appropriate attributes to monitor and set target attribute states in order to determine whether the FMU is progressing toward achieving the defined outcomes. There are a range of required attributes, some of which are common to all water bodies. Authorities need to set appropriate limits on resource use in order to achieve the target attribute states for some of these attributes. Such limits on resource use are likely to include catchment (load or concentration) limits, and also controls on activities that contribute to the exceedance of load limits and target attribute states.

The Bay of Plenty Regional Council (BoPRC) commissioned the University of Waikato to assist with determining the current and potential future state of the water quality-related attributes for sensitive receiving environments in Tauranga Harbour. These receiving environments/regions are outlined in Table 1. The Ministry for the Environment (2021) produced a guide to setting nutrient concentrations in streams, which includes a section specifically targeted to achieving ecosystem health outcomes for estuaries. The key attributes of interest associated with water quality are total nitrogen (TN) and dissolved reactive phosphorous (DRP) which are associated with monitoring outcomes related to ecosystem nuisance growth in nutrient-sensitive environments. Ammonium and nitrate attributes are also monitored, but are related to toxicity effects rather than ecosystem health (although dissolved inorganic nitrogen is often monitored to limit periphyton growth in freshwater). In estuarine systems, primary productivity is generally nitrogen rather than phosphate limited, so the MfE guidance relates to setting limits on nitrogen loading. Although the MfE report recognises its limitations, the Estuarine Trophic Index Toolkit (http://tools.envirolink.govt.nz/dsss/esturine-trophic-index-toolkit/) provides a good starting point to assess the current state of estuarine water quality attributes. In addition, the MfE guidance contains a comprehensive review of the relationship between total nitrogen and estuarine susceptibility to macroalgal and phytoplankton blooms. These are reported in Table 2.

Table 1*: Initial ETI scoping of the Tauranga Harbour sensitive receiving environments provided by the Bay of Plenty Regional Council (Crawshaw et al. 2021).*

Area of Tauranga Harbour	ETI Tool 1 (eutrophication susceptibility)	Nitrogen load susceptibility	BOPRC water quality data & Clues match	ETI Tool 2 (Trophic state)	Tool 2 Macro-algae (EQR) grade	Tool 2 Mud grade
Tauranga Harbour	B	Moderate	Yes	B	B	C
Aongatete Estuary	D	High	Yes – high	B	A	D
Blue Gum Bay	-	-	-	A	A	B
Hunters Creek	-	-	-	B	B	A
Lower Estuary	-	-	-	B	C	A
Mangawhai Estuary	A	Low	No	B	A	D
Matahui West	A	Moderate	No	B	A	D
Middle Estuary	-	-	-	A	A	A
North Estuary	-	-	-	B	B	B
Ongare	-	-	-	C	D	A
Otumoetai	-	-	-	B	C	A
Rangataua Bay	B	Moderate	Yes – low	B	A	B
Rereatukahia Estuary	B	Moderate	Yes – low	C	A	D
Southern Estuary	-	-	-	C	B	C
Te Puna Beach	-	-	-	B	B	A
Te Puna Estuary	C	High	No	C	A	D
Tuapiro Athenree	-	-	-	B	A	A
Tuapiro Estuary	B	Moderate	Yes- high	B	A	C
Upper Estuary	-	-	-	B	A	B
Uretara Estuary	C	Moderate	Yes- high	C	A	D
Waiau Estuary	D	High	Yes – high	A	A	C
Waikaraka Estuary	D	High	No	C	B	D
Waikareao Estuary	D	High	Yes – high	B	A	C
Waimapu Estuary	D	High	Yes – high	B	A	D
Outer Wainui Estuary	-	-	-	C	A	D
Apata	D	Moderate	No	B	A	D
Wainui Estuary	D	Moderate	No	B	A	D
Waipapa Estuary	B	Moderate	Yes – high	C	A	D
Waipu Bay	A	Low	No	B	B	A
Wairoa Estuary	C	High	Yes – matches	B	A	A
Matua	-	-	-	B	A	C
Welcome Bay	C	Moderate	No	B	A	D

The BoPRC has applied the ETI scoping tool to provide an initial assessment of susceptibility to macroalgal blooms (Table 1). Tauranga Harbour is classified as strongly intertidal, and so most susceptible to macro-algae blooms, and so the "macro-algal dominated estuaries" categories are the appropriate attribute state bands to use (listed in Table 2). Following on from this, the brief for this project was to:

(1) Set up a nutrient model and verify the model as much as practicable;
(2) Provide current state conditions (spatially-resolved and summarised for each of the sensitive receiving environments);
(3) Compare the ETI preliminary scoping to the output provided by the new nutrient model;

(4) Model nutrient reduction scenarios and their impact on conditions within the sensitive receiving environments.

Table 2: *Total nitrogen potential state bands (mg/m^3) for susceptibility to phytoplankton and macroalgal blooms (estuaries). The estuarine settings are from Ministry for the Environment (2021). Bands correspond to near reference (A), slightly impacted (B), moderately impacted (C) and heavily impacted (D).*

Receiving Environment	Nutrient	A-Band (mg/m³)	B-Band (mg/m³)	C-Band (mg/m³)	D-Band (mg/m³)
Macroalgal-dominated estuaries	**Potential TN**	**≤ 55**	**> 55 & ≤ 180**	**> 180 & ≤ 350**	**> 350**

2. Study site

Tauranga Harbour is a well-mixed barrier enclosed estuary, or lagoon, with small freshwater inputs relative to its tidal prism. The harbour is enclosed by Matakana Island, and has two entrances, the Mount Maunganui entrance to the south and the Bowentown entrance to the north. The two basins are assumed to behave relatively independently, and are separated by a shallow intertidal area with poor connectivity (Tay et al., 2013, Spiers et al., 2009). Currents are highly channelized by naturally-scoured channels which have been shaped by the geological features such as island and peninsulas. A large volume of water flows in and out of the harbour over each tide, and the estuarine plume generally extends ~3.5 km seaward (Spiers et al., 2009). The surrounding topography is steep and complex (Mullan, 1996) and weather can be strongly influenced by El Niña-La Niño cycles (Salinger & Mullan, 1999). Mean annual rainfall is approximately ~1200 mm (Stokes et al., 2010), with wetter months in June to August. The dominant wind direction is from the southwest (Tay et al., 2013). The largest freshwater source into the estuary is the Wairoa River (~60% of surface water discharge). The total catchment area of the harbour is 1300 km^2, which is predominantly agricultural (34.4), indigenous forest (29.7%), exotic forest (11.9%) and horticultural (5.9%) (BoPRC, 2018 landuse cover map).

3. Methods

3.1 Model setup

The modelling suite used for this study was provided by Deltares and included the Delft3D-FLOW model and the DELWAQ water quality model. These models were used because they are freely available, well documented and there is a large international community that currently uses these models. The Delft3D-FLOW model was the hydrodynamic driver for the water quality model, and the flow model runs (which were relatively computationally expensive) were completed prior to running the DELWAQ model. The water quality model was coupled to the higher resolution hydrodynamic outputs with a coarser aggregated grid, which made simulation times substantially faster. The governing equations used in these models and modules are described further in detail in Deltares (2017, 2018). The Delft3D model was set up in previous studies of the harbour: Stewart (2021) for the southern basin and de Ruiter et al. (2019) for the whole harbour, and the same model set up was used for this study. Both these studies performed extensive calibration exercises, so these were not replicated here. The Delft3D model solves the unsteady shallow water equations and was developed specifically for regional studies, and thus can be applied in lakes, estuaries, shallow seas, and rivers. Here, we used a 2D depth-averaged model, due to the shallow nature of the harbour and evidence from past studies of little stratification. Since there was a lot of variation between years in Tauranga Harbour, and harbour flushing and salinity regimes were very sensitive to the number of events (for example, changing between strongly El Niño and La Niña years (Stewart, 2021)), we decided to model multiple years of summer and winter conditions. In each case, the model was set up to run for 3 months (a total of ten 3-month blocks), and these runs were used to force the water quality model. The runs started in winter 2015 and finished in summer 2019/2020. It should be noted that between mid-2015 and early 2016 the climate was in an El Niño phase, whereas the remaining years in the modelled period were predominately in a neutral climate phase. The period between 2015-2020 also coincided with more consistent monitoring data from estuarine monitoring stations, which were used for verification of the model.

Stages for setting up the numerical models were: setting up the model grid and bathymetry; forcing the hydrodynamic model using tides, salinity, winds, pressure, rain, and river discharge as forcing; coupling the hydrodynamic model output to the water quality model; forcing the water quality model with nutrient concentrations at the ocean and river boundaries and outputting the water quality parameters for verification/analysis.

3.2 Model domain and grid

The 2D hydrodynamic model was constructed with 4 domains (one large, one intermediate and two small, Figures 1 and 2), which were connected using domain-decomposition. Domain decomposition takes the output of the larger model, and uses it as open boundary forcing for the smaller model (Figure 2a). The outer boundary was set at 30 km offshore, to make sure that the model captures dilution of water in the shelf, and also to ensure that the outer boundary could be forced with salinity values associated with true open ocean conditions. This is because there are no good measurements or model outputs for salinity in the coastal ocean. The model was depth-integrated, and tests with the fully 3D-model indicated very little improvement in accuracy is gained by moving to a 3-dimensional model (<1%) (Stewart, 2021).

The large domain was approximately 400×400 m and it had 3 open ocean boundaries. The intermediate grid had a grid cell resolution of 100×100 m, which was chosen so as to transition between the outer and inner grids, and to make sure that the model remained stable during that transition. The inner harbour models had grid resolutions of 25×25 m. The finer resolution was essential in order to resolve the complex series of channels, islands and sub-estuaries within the harbour. The bathymetry (Figure 2b) for each of the grids was interpolated from various sources. The offshore grids used the LINZ hydrological charts, NZ 541 and NZ 5411 (2016). The harbour domain used a combination of data from multiple sources including: multibeam, LiDAR (Light Detection and Ranging) and LINZ hydrological charts NZ 5411 (2016). All of these were converted from their respective datums (the LINZ data are relative to chart datum which is 1.05 below mean sea level (lowest astronomical tide)) to mean sea level.

Clusters of the finer hydrodynamic grid cells from the Delft 3d-FLOW model were merged using DIDO, a grid aggregation program, to create larger aggregated volumes for Delft3D-WAQ simulations (Figure 1). The two harbour domains were clustered in groups of approximately 3 x 3 grid cells (75m grid resolution), whereas the intermediate and outer grids were clustered in groups of approximately 6 x 6 cells (600m – 1200m grid resolution).

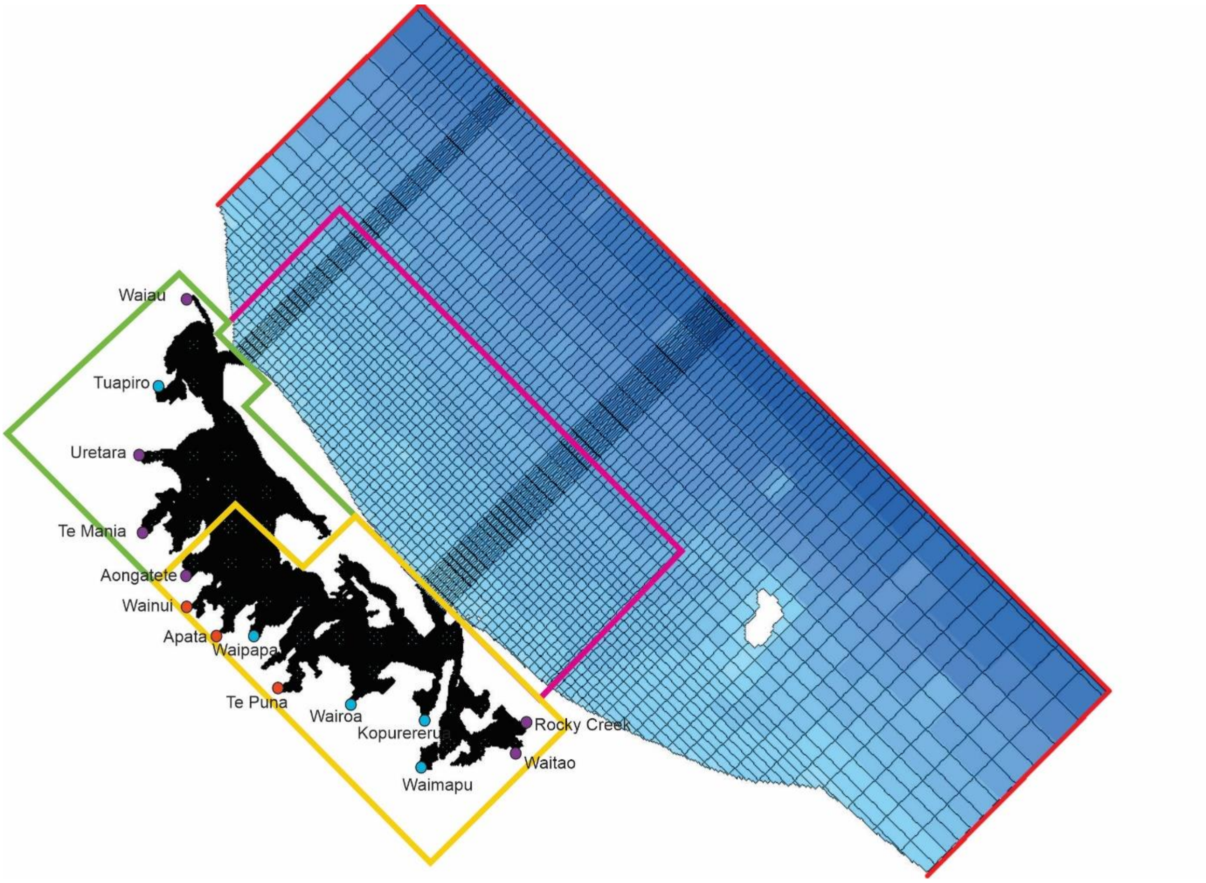

***Figure 1**: The 4 model domains used in the hydrodynamic model coupled with the aggregated water quality grid (shown above), with: The outer grid; Magenta: Intermediate grid; Green: The north harbour; Yellow: The south harbour. The river discharge points are marked (Blue: automatically gauged; Purple: intermittently measured; Orange: unmeasured.)*

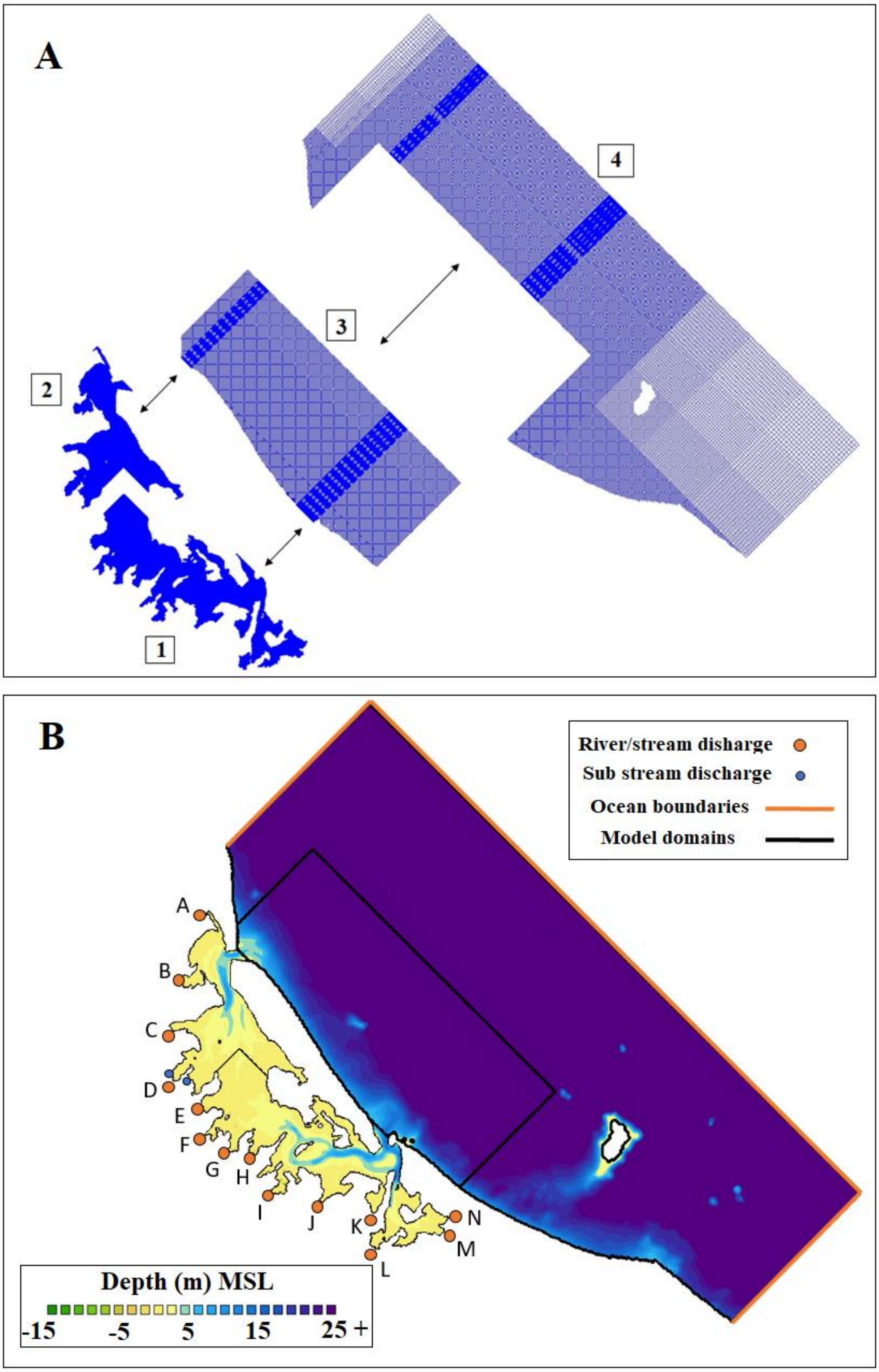

***Figure 2**: (A): Higher resolution hydrodynamic model grids and how the 4 model domains interact. (B) composite bathymetry used in the model, symbols and markers illustrate discharge and open boundaries used for forcing of the model.*

3.3 Boundary conditions and forcing

3.3.1 Tidal ocean boundary

The open ocean boundary was forced using the 13 main harmonic tidal constituents derived from the NIWA tide model (Walters et al., 2001). These were applied as an amplitude and phase at the shore-parallel boundary of the larger oceanic domain, and the model recreates the water level at this boundary from these constituents depending on the period of time over which the model is run. Neumann boundaries were used at the two shore-perpendicular boundaries. A reflection parameter (alpha) value of 50 was applied at the open boundary to stop internal reflections of the tide within the model. The higher resolution grids were forced by the water level conditions generated from the larger grids as well as 10 river discharge points, representing the main river and creek flow inputs into the southern basin of the harbour (shown on Figures 1 and 2b), described in the next section.

3.3.2 Rivers and stormwater

Discharge input to the model was provided from the continuous flow data collected by BoPRC at Wairoa, Waimapu, Kopurererua, Waipapa, and Tuapiro, input as a daily average rate in m^3/s. Intermittent flow measurements were taken at the remaining six river and creek systems (Waitao, Aongatete, Te Mania, Uretara, Rocky stream), or were ungauged (Te Puna, Apata, Wainui). Due to the similarity in rainfall and other characteristics across the catchments, a regression model was used to predict the intermittently-observed sites from the gauged sites. Once the regression model was created, then this was applied to continuous monitoring data to predict continuous discharge data at the intermittent sites (these are all shown in Appendix 2, with an example provided in Figure 3). For the sites with no measurements, all available data were used to develop a relationship between discharge and catchment size and this was used to determine which of the gauged catchments to use as a proxy.

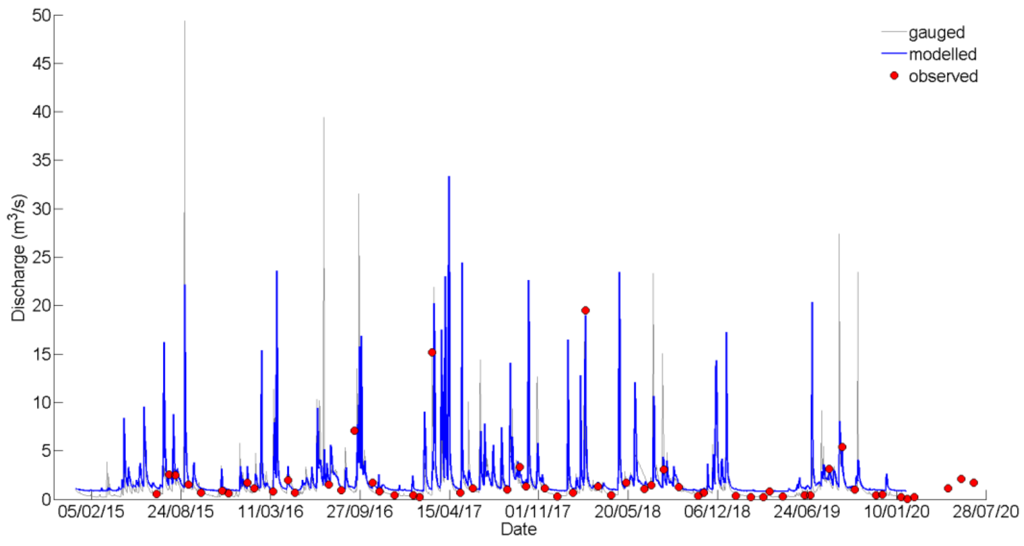

***Figure 3**: The predicted river discharge for the Aongatete River using the gauged Taupiro river discharge data as a predictor (other river predictions are provided in Appendix 2).*

3.3.3 Winds, rainfall and evaporation

Wind speed, wind direction, rainfall and evaporation timeseries were created from weather information extracted from the MetService Tauranga automated weather station (AWS).

These timeseries were applied uniformly across the whole domain. Wind speed and direction changed the circulation patterns, particularly in the two high resolution domains, whereas rainfall and evaporation were needed to help predict salinity variations correctly.

3.3.4 Salinity

With a flushing time in the inner harbour of up to 10-12 days, it could take many months of model time to mix away initial salinity gradients and reach a more realistic salinity field. In other words, the model output was sensitive to the initial salinity assumptions in the model. Therefore, we started with a more realistic spatial variation in salinity by using observations collected by the BoPRC monitoring team at harbour site locations. We used these observations to set initial salinity values in different harbour sub regions (by assigning values to defined polygon regions) for summer and winter over the different years. Seasonal CTD casts taken on the ebb and flood tide by Port (Port, 2016), which included 8 salinity surveys of the southern harbour over a year, were also used as further verification. Determining appropriate values to set salinity at the offshore boundary was also problematic, because salinity at the harbour entrance is strongly influence by mixing with the shelf water (although unknown, we expect the inner shelf has lower salinity than the open open). Salinity is also not well predicted by regional models (such as from Moana project output) because in order to make realistic predictions, freshwater discharge and tidal mixing in estuaries needs to be modelled. As stated previously, in order to overcome this challenge, we extended the outer model boundary to the shelf break where we can expect open ocean conditions. To parameterise the salinity here, we used observations from three separate ARGO drifter sensor (D5904537) profiles, which visited the offshore boundary waters between 19/8/2014 – 17/4/2015. In addition, a historical offshore deployment and transects (~100 survey sites between -36.503049°, 176.242501° and -37.450446°, 177.996782°) reaching 200km offshore taken between1982 – 2016 were provided by NIWA (Bell & Chiswell, 2017 pers. comm.). All these were combined to make a seasonal climatology of offshore water salinity, which was used to inform the open boundary conditions. In the end, the observed salinity only ranged between 34.5 – 35.6.

3.4 Flushing time evaluation

Flushing time was evaluated in the model by seeding a region of interest with a passive neutrally buoyant conservative tracer, with a concentration of 1 g/m^3 (the initial amount is arbitrary). The tracer content of water coming at river discharge points and at the open boundary, and all other regions, were set to zero. The tracer was then output either everywhere in the grid, or at observation points. The output of tracer decays with time as it is flushed out of the region of interest (Figure 4). The flushing rate can be quantified by fitting an exponential curve to the decay of tracer, and the exponential decay rate becomes the measure flushing rate. The rate is in days^{-1}, and the flushing time is the inverse of the flushing rate. A high flushing rate means that the estuary is well-flushed, with a low flushing time.

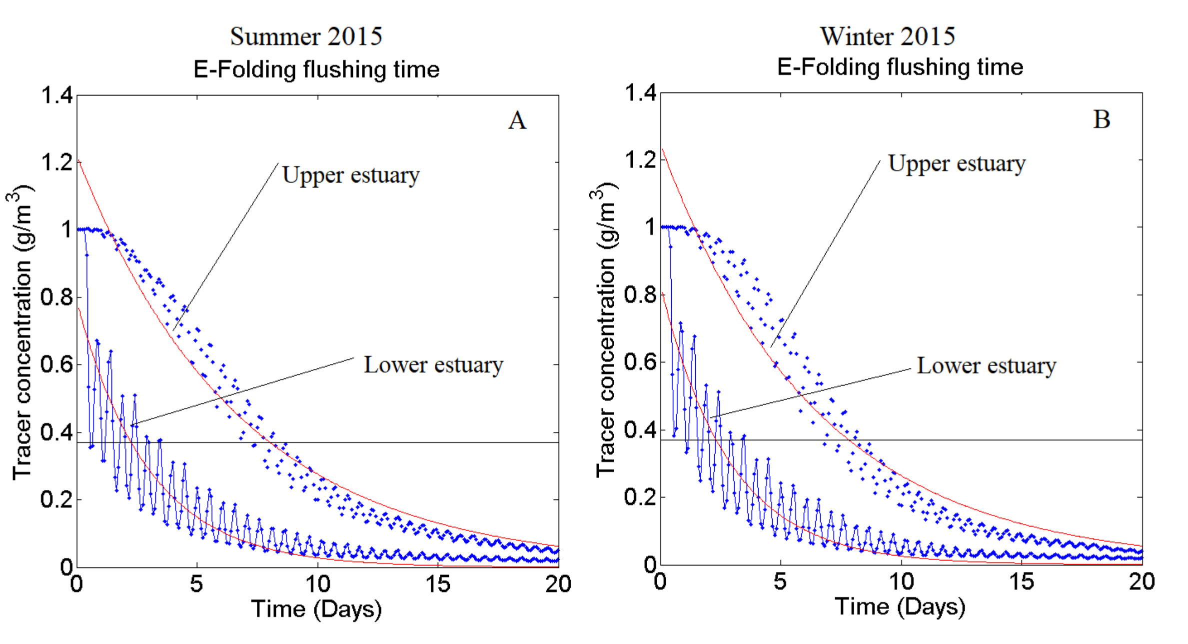

Figure 4: *Example (from summer 2015 (left) and winter 2015 (right) of how the flushing time is evaluated.*

3.5 Calibration and Validation of Hydrodynamic Model

Calibration of the bottom roughness and verification of the bathymetry were undertaken by comparing hydrodynamic model output with available water level and current gauges. The timing and approximate amplitude of the tide was first verified to ensure that the channels in the high-resolution model were well represented. Where channels are diagonal to the model grid, and where narrow entrances to sub-estuaries of the harbour were located at a diagonal to the model grid, it was necessary to manually adjust the bathymetry so water could flow freely into these locations. Once the general behaviour of the tide was verified, then detailed calibration was undertaken by adjusting the spatially-varying bottom roughness and by minimising the error between model output and current and water level observations. The model was calibrated as part of de Ruiter et al (2019), and results are also summarised here. Observations from October and November 2015 were used from 13 stations for calibration and verification (Figure 5, black and green dots). An example of the fit between model and data is given in Figure 6. An overview of how the calibration statistics were calculated is provided in the Appendix 4. In general, the model skill was in the category “excellent” with some current values in the “good” or “reasonable” category (Tables 3 and 4). Manning coefficient values were between 0.02 and 0.1 $s/m^{1/3}$ in the final model set-up.

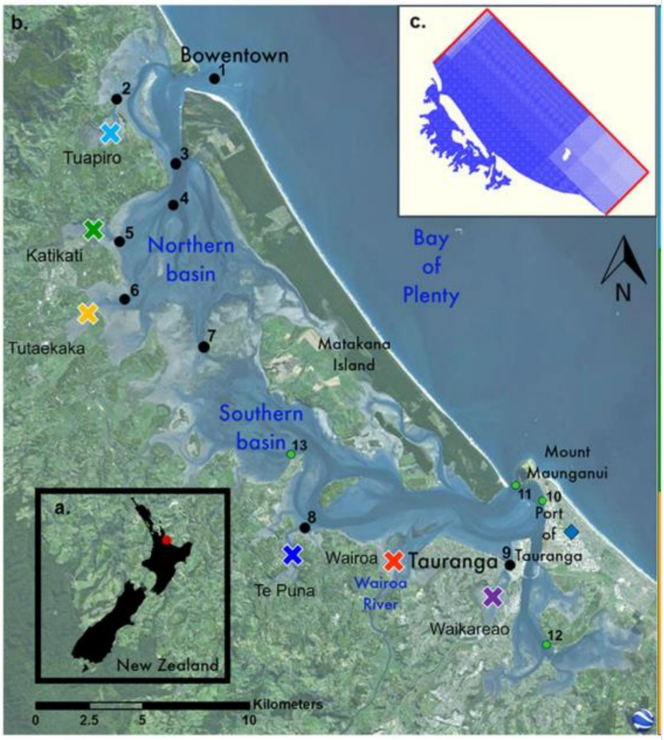

Figure 5*: Location of observations used for calibration and verification of the northern harbour model (reproduced from de Ruiter et al. (2019).*

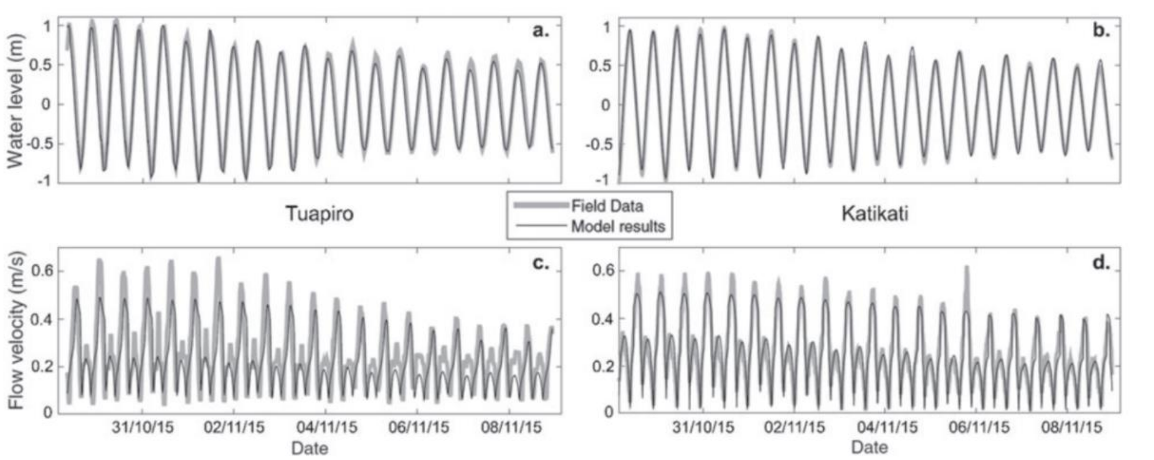

Figure 6*: Comparison between model and data for the northern harbour calibration (reproduced from de Ruiter et al., 2019).*

Table 3*: Average mean and standard deviations of model accuracy (RMSE, MAE) and skill (BSS) values averaged for the northern harbour model (reproduced from de Ruiter et al., 2019).*

	Water level		Current speed	
Parameter	Mean	SD	Mean	SD
RMSE (m)	0.094	0.022	0.112	0.030
MAE (m)	0.070	0.014	0.101	0.034
BSS	0.973	0.012	0.532	0.257

Table 4: *Location specific calibration statistics of model accuracy (RMSE, MAE) and skill (BSS) values for the northern harbour model (reproduced from de Ruiter et al., 2019). Locations are shown in Figure 5 and missing*

values are indicated by '-'. The colours mean Excellent (dark green), Good (light green), Reasonable (yellow), Poor (orange).

	Water Level	**Current speed**
Location	BSS	BSS
1	0.98	0.82
2	0.97	0.4
3	0.96	0.15
4	0.99	0.84
5	0.98	0.55
6	0.98	0.22
7	0.95	0.45
8	0.98	-
9	0.98	0.54
10	0.98	-
11	-	0.82
12	0.96	-
13	0.97	-

3.6 Biogeochemical model

The DELWAQ water quality model was used to simulate the biogeochemical processes within the harbour. The model was set up using a simple configuration, to simulate the nitrogen and phosphate cycles and one pelagic (green) phytoplankton (Chl-a) group (Table 5). Input of nutrients was accomplished by setting the concentrations of nutrient and algae at all the freshwater discharge points and of the open boundaries. Discharges were set by using the BoPRC monitoring data (average concentrations for each of the 3-month modelling periods were used, which were combined with the discharge within the model to make time-varying loading). The frequency of monitoring data changed between sites, but was on the order of monthly. The open boundaries were set using the values observed at the southern entrance to the harbour (which is one of the estuarine monitoring stations). The dissolved inorganic part of the nitrogen cycle model included nitrification of ammonia to nitrate in the water column, denitrification in the sediments, uptake (during growth) and release (during mortality) of nitrogen by the phytoplankton, and diffusive waste of ammonia. Dissolved inorganic phosphate included uptake and release from phytoplankton growth and mortality, and diffusive waste. Organic nitrogen and phosphate were simulated as part of composition and decomposition of phytoplankton, and finally, phytoplankton were simulated with growth (depending on light, salinity, temperature (a constant) and nutrient availability) and mortality. Although there was no grazing, recruitment or other elements of the food web added, these are essentially modelled by increasing or decreasing the mortality rate of the phytoplankton group (the mortality rate is an arbitrary parameter).

***Table** 5: List of substances and processes included in the water quality model simulations*.

Substances	Selected processes
Salinity	
NH4	Nitrification of ammonium Uptake of nutrients by growth of algae Release of nutrients by mortalility algae diffuse waste flux of NH4 (option)
NO3	Denitrification in sediment Nitrification of ammonium Uptake of nutrients by growth of algae
PO4	Uptake of nutrients by growth of algae release of nutrients by mortality of algae Diffusive waste PO4 (option)
DON DOP PON1 (fast decomposing) POP1 (fast decomposing)	Composition Composition Release (nutrients/detritus) by mortality of algae Release (nutrients/detritus) by mortality of algae
Algae (green - no diatoms)	Net Primary production and mortality of green algae

There are a wide range of parameters that are needed for even this simple biogeochemical model, and we set these as the defaults unless we had locally-relevant data. Local measurements were used to set the ambient water temperature (BoPRC monitoring data), the light extinction coefficient (Cussioli et al. 2019), and the denitrification rates (from G. Flower's PhD experimental work). The light conditions needed in the model (for the algal growth component) were obtained from the BoPRC solar radiation monitoring site, and these were adjusted for the difference in daylight hours between winter and summer. Table 6 shows the parameter values that were used.

__Table 6__: Set up of biogeochemical model (summer and winter scenarios)

Processes		**SUMMER scenarios**	**WINTER scenarios**	
Variable	**Description**	**Value**	**Value**	**Unit**
NCRatGreen	N/C ratio greens	0.16	0.16	(g N/g C)
CRatGreen	P/C ratio greens	0.02	0.02	(g P/g C)
FrAutGreen	Fraction autolysis greens	0.3	0.3	-
FrDetGreen	Fraction to detritus by mortality greens	0.7	0.7	-
NH4KRIT	Critical NH4 concentration	0.01	0.01	(gN/m3)
OXY	Dissolved Oxygen	7.5	9	g/m3
RcNit20	MM-nitrification rate at 20 C	0.005	0.005	gN/m3/d
RcNit	first-order nitrification rate	0.005	0.005	1/d
TcNit	temperature coefficient for nitrification	1.07	1.07	-
KsAmNit	half saturation constant for ammonium co	0.5	0.5	gN/m3/d
KsOxNit	half saturation constant for DO cons	1	1	g/m3
Temp	ambient water temperature	20	15	C
CTnIT	critical temperature for nitrification	3	3	C
COXNIT	critical oxygen concentration for nitrification	1	1	g/m3
Poros	volumetric porosity	1	1	
OOXNIT	optimum oxygen concentration for nitrification	5	5	gO2/m3
RcDENSed	first order denitrification rate in the sediment	0.1	0.1	m/d
TcDEN	temperature coefficient for denitrification	1.12	1.12	-
CTDEN	critical temperature for denitrification	2	2	C
PPMaxGreen	Maximum production rate Greens	1.4	1.4	1/d
GRespGreen	growth respiration factor Greens	0.15	0.15	-
st.tem	Maintenance respiration Greens	0.045	0.045	
Mort0Green	Mortality rate constant greens	0.35	0.35	1/d
MortSGreen	Mortality rate Greens at high salinity	0.35	0.35	1/d
SalM1Green	Lower salinity limit for mortality G	5	5	g/kg
SalM2Green	upper salinity limit for mortality G	40	40	g/kg
MinGreen	Minimum level Greens in mortality	0.015	0.015	gC/m3
Grtochl	Chlorophyll-a:C ratio in Greens	50	50	mg Chlfa/g C
DayL	daylength <0-1>	0.58	0.416	D
OptDLGreen	daylength for growth saturation of Greens	0.58	0.58	D
-	Ammonium preference over nitrate Greens	1	1	-
KMDINgreen	half-saturation value N Greens	0.005	0.005	gN/m3
KMPgreen	half saturation value P Greens	0.001	0.001	gP/m3
RadSatGree	total radiation growth saturation greens	80	80	W/m2
TcGroGreen	temperature coeff. For growth process	1.04	1.04	-
TcDecGreen	temp coeff. For respiration and mortality	1.07	1.07	-
RadSurf	irradiation at the water surface	300	92.6	W/m2
a_enh	enhancement factor in radiation calculation	1.5	1.5	-
fRefl	fraction of radiation reflected at water surface	0.05	0.05	-
ExtVLBak	background extinction of visible light	1	1	1/m
Zthreshold	depth threshold for emersion	0.01	0.01	M

4. Results and discussion

Results are presented in 5 sections. In the first section, the regional variations of current state conditions are presented (Section 4.1.1). Then aim of Section 4.1.2 is to determine whether the uncalibrated model parameters (salinity, flushing time, nutrients (NO_3^-, NH_4^+, PO_4^{3-}, TN, ON, OP, Chl-a) provided realistic predictions of the conditions in the harbour. After this, in Section 4.1.3, a sensitivity analysis was conducted to determine which parameters have the greatest effect of nutrient levels. Section 4.1.4 reports on an analysis of the sources and sinks within each region of the harbour. Finally, reduction scenarios are provided (Section 4.2), where the concentration at the discharge points is reduced by arbitrary amounts of 20% and 40% to assess how broad scale change might affect nutrient conditions in the harbour.

4.1 Current State (Baseline) Results

4.1.1. Spatial variation of current state conditions

Large spatial variations existed in the model domain (summarised in Figures 7 and 8 and Tables 7 and 8), largely reflecting the change in flushing time between the two entrances and the centre of the basin, combined with proximity to freshwater inputs (which carried the nutrient loading), and nutrient cycling within the estuary (mainly caused by algal uptake and denitrification). Table A1 in Appendix 7 summarises the physical characteristics. The southern basin was more enriched with nutrients, mainly because there were greater discharges of freshwater in the southern basin. Differences between winter and summer were not large, and were generally caused by increased freshwater discharge in the winter months. The largest impact areas for nutrients were in proximity to the Wairoa River followed by the Kopurereroa and the Waimapu — the latter two having a larger effect because they discharge into poorly-mixed regions. Rangataua Bay appears to be disproportionately high in ammonium in winter, even though it is a shallow area with low freshwater input and relatively high denitrification (see source analysis in Section 4.1.4). This is likely due to the higher than normal concentration of ammonium in Rocky Stream (the main freshwater input). Phosphate and summer nitrogen inputs are much higher in the 3 main southern basin discharges. Tables 9 and 10 shows the average nutrient concentration of each discharge used in the modelling.

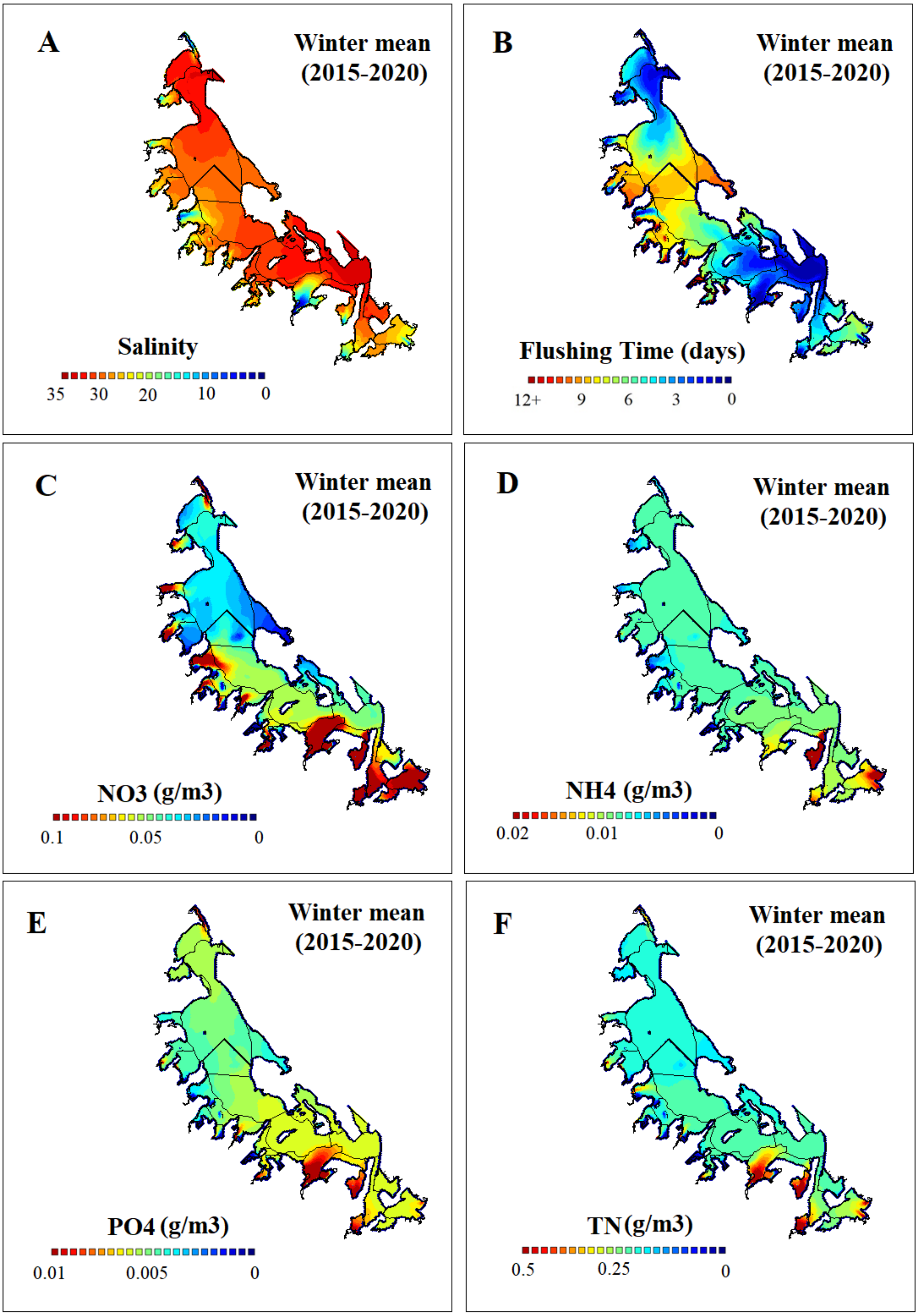

Figure 7*: Spatial maps of (A) salinity, (B) flushing time, (C) NO_3^-, (D) NH_4^+, (E) PO_4^{3-}, (F) TN for winter.*

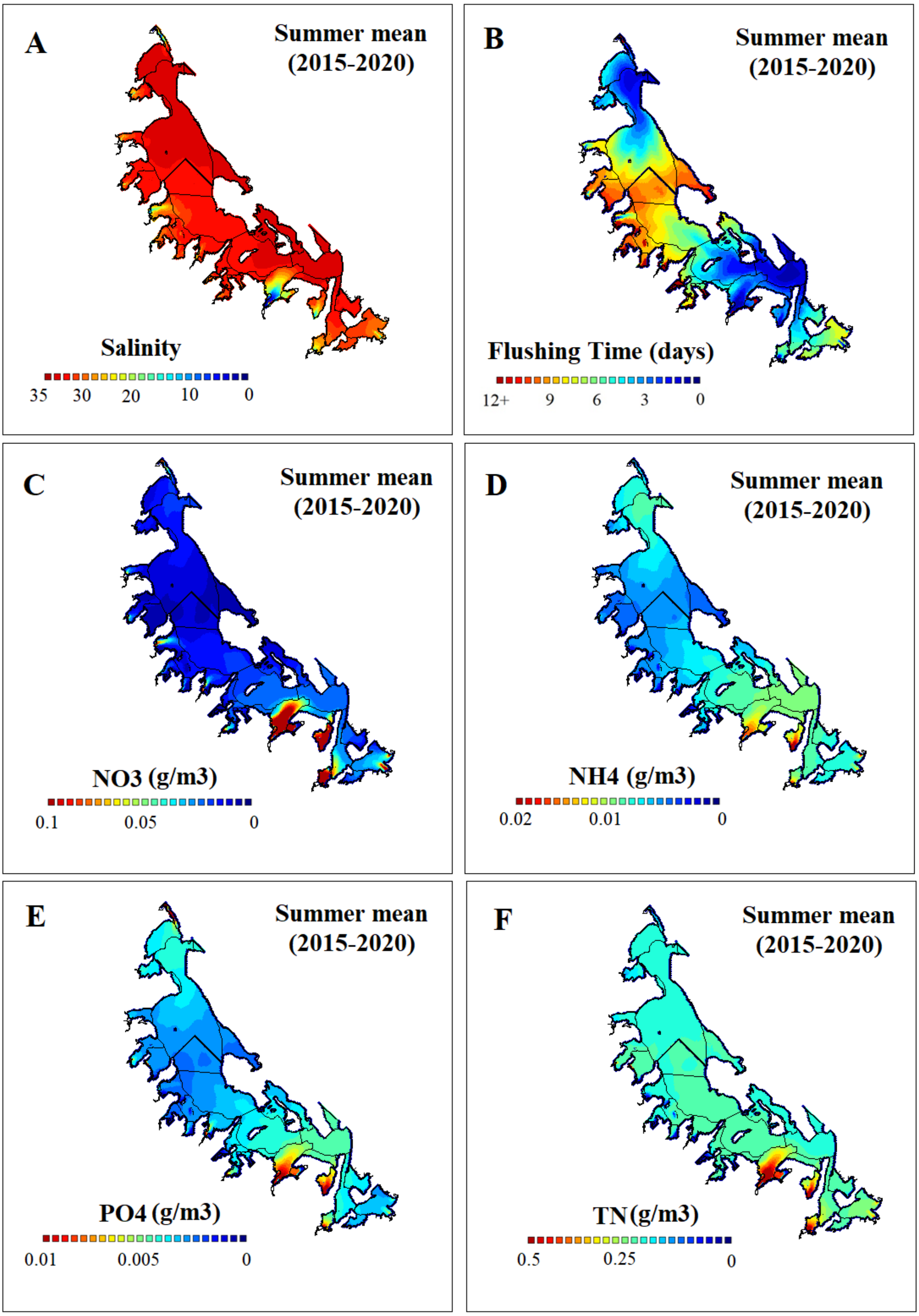

Figure 8*: Spatial maps of (A) salinity, (B) flushing time, (C) NO_3^-, (D) NH_4^+, (E) PO_4^{3-}, (F) TN for summer.*

Table 7: Table of characteristics output from biogeochemical modelling for winter conditions. See Appendix1 for the location of each numbered region.

Estuary Sub Region	ID	Mean Salinity (ppt)	STD (ppt)	Mean Flushing Time (days)	STD (days)	Mean NO3 (g/m³)	STD (g/m³)	Mean NH4 (g/m³)	STD (g/m³)	Mean NH4 (g/m³)	STD (g/m³)	Mean TN (g/m³)	STD (g/m³)
Aongatete	1	19.81	5.45	7.04	5.10	0.118	0.087	0.006	0.002	0.004	0.001	0.219	0.095
Hunters Creek	21	31.85	1.27	4.58	3.00	0.037	0.014	0.009	0.002	0.006	0.001	0.201	0.054
Lower Estuary	2	33.42	0.51	0.83	0.52	0.054	0.011	0.010	0.001	0.006	0.001	0.229	0.031
Mangawhai Estuary 1	14	30.50	0.76	6.44	1.44	0.047	0.016	0.009	0.002	0.006	0.001	0.211	0.041
Mangawhai Estuary 2	15	24.92	1.96	19.88	6.32	0.002	0.001	0.001	0.001	0.001	0.001	0.025	0.018
Otumoetai	6	32.01	1.24	2.42	0.59	0.084	0.029	0.013	0.005	0.007	0.001	0.256	0.053
Rangataua Bay	10	24.86	2.43	5.57	1.85	0.125	0.061	0.016	0.010	0.006	0.001	0.290	0.084
Southern Estuary	24	28.62	2.33	3.70	1.47	0.108	0.051	0.011	0.003	0.006	0.002	0.270	0.074
Te Puna Beach	5	31.41	0.19	4.10	0.68	0.061	0.009	0.010	0.001	0.006	0.001	0.234	0.032
Te Puna Estuary 1	12	29.48	1.66	6.71	3.87	0.064	0.026	0.009	0.002	0.006	0.001	0.221	0.054
Te Puna Estuary 2	13	24.69	4.75	7.90	6.42	0.164	0.125	0.008	0.003	0.007	0.003	0.272	0.132
Waikareao	7	25.48	4.64	2.91	2.47	0.292	0.187	0.057	0.029	0.009	0.003	0.499	0.228
Waikaraka Estuary	11	29.63	2.07	10.24	7.57	0.029	0.020	0.007	0.004	0.004	0.003	0.150	0.088
Waimapu Estuary	8	19.91	3.02	2.95	1.84	0.364	0.168	0.013	0.004	0.008	0.002	0.491	0.184
Wainui Estuary 1	22	27.56	1.51	8.74	2.64	0.052	0.019	0.009	0.002	0.005	0.001	0.206	0.045
Wainui Estuary 2	17	26.13	2.30	10.66	6.74	0.069	0.070	0.007	0.003	0.004	0.002	0.176	0.107
Apata (Wainui Estuary 3)	18	23.41	3.35	9.98	6.74	0.079	0.068	0.006	0.003	0.004	0.002	0.181	0.094
Waipapa Estuary	16	28.31	3.14	7.34	3.25	0.082	0.072	0.009	0.002	0.006	0.002	0.237	0.069
Waipu Bay	23	30.52	0.67	4.20	1.42	0.061	0.016	0.010	0.002	0.006	0.001	0.227	0.048
Wairoa 1	3	20.41	8.69	2.03	1.19	0.227	0.118	0.011	0.001	0.009	0.002	0.374	0.105
Wairoa 2	4	17.70	2.92	3.86	4.72	0.220	0.106	0.010	0.004	0.010	0.003	0.328	0.142
Welcome Bay	9	26.47	1.25	6.41	3.99	0.076	0.031	0.010	0.003	0.006	0.002	0.226	0.080
Middle Estuary	20	31.56	0.63	3.34	1.29	0.059	0.009	0.010	0.001	0.006	0.001	0.234	0.025
Upper Estuary	19	28.83	1.85	6.89	1.22	0.059	0.011	0.010	0.001	0.006	0.000	0.229	0.014
North Domain	25	30.63	1.50	5.43	2.42	0.036	0.006	0.010	0.001	0.005	0.001	0.211	0.022
Matahui West	26	27.82	0.88	9.87	3.86	0.102	4.569	0.013	0.243	0.012	0.374	0.398	8.799
Rereatukahia Estuary	27	26.04	3.59	8.16	2.92	0.104	1.062	0.010	0.022	0.006	0.034	0.274	1.320
Uretara Estuary	28	24.03	4.04	5.71	3.03	0.090	0.056	0.007	0.002	0.004	0.001	0.213	0.056
Blue Gum Bay	29	28.93	0.53	8.95	2.47	0.018	0.007	0.009	0.002	0.004	0.001	0.187	0.037
Ongare	30	32.32	0.34	3.96	0.68	0.036	0.009	0.009	0.002	0.005	0.001	0.205	0.048
Tuapiro Estuary	31	24.51	5.23	3.40	3.21	0.055	0.027	0.007	0.002	0.005	0.001	0.172	0.050
Tuapiro Athenree	32	31.95	1.33	3.99	1.73	0.038	0.017	0.009	0.001	0.006	0.001	0.205	0.034
Waiau Estuary	33	13.63	9.93	1.56	1.98	0.201	0.106	0.007	0.002	0.009	0.003	0.299	0.109
Central (Part of Northern)	34	28.41	0.61	8.23	1.66	0.039	0.010	0.009	0.001	0.005	0.001	0.205	0.032

Table 8: Table of characteristics output from biogeochemical modelling for summer conditions. See Appendix1 for the location of each numbered region.

Estuary Subregion	ID	Mean Salinity (ppt)	STD (ppt)	Mean Flushing Time (days)	STD (days)	Mean NO3 (g/m³)	STD (g/m³)	Mean NH4 (g/m3)	STD (g/m³)	Mean PO4 (g/m3)	STD (g/m³)	Mean TN (g/m3)	Standard Deviation (g/m³)
Aongatete	1	27.17	3.73	9.86	5.13	0.020	0.020	0.005	0.001	0.002	0.001	0.187	0.053
Hunters Creek	21	33.72	0.58	4.80	3.14	0.011	0.006	0.007	0.002	0.003	0.001	0.207	0.054
Lower Estuary	2	34.31	0.36	0.82	0.47	0.023	0.005	0.010	0.001	0.005	0.001	0.221	0.030
Mangawhai Estuary 1	14	32.61	0.30	7.02	2.24	0.013	0.005	0.007	0.001	0.003	0.001	0.219	0.030
Mangawhai Estuary 2	15	29.78	1.74	22.04	5.50	0.002	0.000	0.002	0.001	0.001	0.000	0.053	0.032
Otumoetai	6	33.29	0.93	2.39	0.62	0.037	0.015	0.010	0.002	0.005	0.001	0.239	0.046
Rangataua Bay	10	29.59	1.65	6.22	1.91	0.033	0.021	0.008	0.002	0.003	0.001	0.246	0.055
Southern Estuary	24	31.60	1.38	3.89	1.63	0.036	0.018	0.009	0.002	0.004	0.001	0.241	0.061
Te Puna Beach	5	32.99	0.12	4.30	0.68	0.022	0.003	0.009	0.001	0.004	0.001	0.230	0.032
Te Puna Estuary 1	12	32.31	1.05	7.32	4.24	0.017	0.007	0.007	0.002	0.004	0.001	0.215	0.049
Te Puna Estuary 2	13	29.55	4.86	9.49	5.47	0.040	0.042	0.006	0.002	0.005	0.003	0.208	0.074
Waikareao	7	27.64	4.48	3.27	3.26	0.167	0.133	0.014	0.006	0.008	0.003	0.353	0.147
Waikaraka Estuary	11	32.08	1.25	10.48	6.93	0.008	0.006	0.006	0.003	0.003	0.001	0.165	0.083
Waimapu Estuary	8	26.00	2.31	4.59	2.19	0.142	0.085	0.010	0.003	0.005	0.002	0.375	0.138
Wainui Estuary 1	22	31.54	0.74	9.61	2.69	0.009	0.003	0.006	0.001	0.002	0.000	0.213	0.039
Wainui Estuary 2	17	30.79	1.39	12.41	6.18	0.015	0.017	0.004	0.002	0.003	0.001	0.170	0.084
Apata (Wainui Estuary 3)	18	29.49	1.98	12.16	5.49	0.014	0.013	0.004	0.001	0.002	0.001	0.175	0.072
Waipapa Estuary	16	31.68	1.86	8.40	2.97	0.019	0.020	0.007	0.001	0.003	0.001	0.222	0.041
Waipu Bay	23	32.78	0.34	4.33	1.53	0.018	0.006	0.009	0.002	0.004	0.001	0.220	0.045
Wairoa 1	3	23.35	8.65	2.54	1.57	0.115	0.079	0.012	0.002	0.007	0.002	0.382	0.125
Wairoa 2	4	22.64	3.21	6.30	7.83	0.100	0.055	0.010	0.004	0.007	0.003	0.356	0.153
Welcome Bay	9	30.57	0.62	6.89	4.13	0.019	0.008	0.007	0.002	0.003	0.001	0.217	0.072
Middle Estuary	20	33.15	0.37	3.41	1.41	0.021	0.004	0.009	0.001	0.004	0.001	0.229	0.025
Upper Estuary	19	32.11	0.76	7.45	1.44	0.012	0.003	0.007	0.001	0.003	0.000	0.228	0.013
North Domain	25	33.83	0.51	5.21	2.65	0.009	0.004	0.007	0.002	0.003	0.001	0.219	0.022
Matahui West	26	32.95	0.61	10.40	3.48	0.043	2.557	0.009	0.310	0.010	0.456	0.450	13.041
Rereatukahia Estuary	27	31.68	3.84	9.17	3.20	0.015	0.141	0.005	0.010	0.003	0.015	0.232	0.382
Uretara Estuary	28	30.64	2.79	7.37	2.97	0.014	0.012	0.005	0.001	0.003	0.001	0.194	0.044
Blue Gum Bay	29	33.70	0.33	9.43	2.55	0.002	0.001	0.004	0.001	0.002	0.000	0.216	0.042
Ongare	30	34.39	0.10	3.41	0.61	0.012	0.003	0.008	0.002	0.004	0.001	0.206	0.048
Tuapiro Estuary	31	30.11	4.41	4.60	3.93	0.010	0.004	0.006	0.002	0.004	0.001	0.173	0.049
Tuapiro Athenree	32	34.21	0.66	3.67	2.06	0.010	0.004	0.008	0.001	0.004	0.001	0.205	0.029
Waiau Estuary	33	19.97	11.31	3.27	5.18	0.037	0.027	0.007	0.002	0.009	0.004	0.167	0.058
Central (Part of Northern)	34	32.59	0.35	8.83	1.84	0.005	0.002	0.005	0.001	0.002	0.000	0.220	0.033

Table 9: *Average discharge and nutrient concentration of the timeseries used to force the biogeochemical model at each of the freshwater discharge points (for summer).*

	Summer										
River or stream ID	**Flows (m^3/s)**				**Average Nutrient concentration (g/m^3)**						
	Mean	**min**	**max**	**std dev**	**NH4**	**NO3**	**DRP (PO4)**	**DON**	**DOP**	**TN**	**TP**
Uretara	0.599	0.151	4.259	0.639	0.005	0.100	0.004	0.054	0.006	0.158	0.010
Tuapiro	1.085	0.290	10.585	1.565	0.003	0.030	0.005	0.084	0.009	0.117	0.014
Te Mania	0.294	0.104	2.169	0.319	0.008	0.165	0.006	0.089	0.010	0.262	0.016
Waiau	0.629	0.219	6.553	0.959	0.007	0.116	0.014	0.103	0.019	0.225	0.033
Wairoa	14.492	6.496	93.296	12.736	0.017	0.342	0.011	0.350	0.051	0.709	0.062
Te Puna	0.282	0.040	3.654	0.568	0.009	0.328	0.017	0.072	0.014	0.410	0.031
Wainui	0.355	0.050	4.597	0.715	0.005	0.158	0.003	0.073	0.005	0.236	0.008
Aongatete	1.380	0.375	13.356	1.973	0.005	0.158	0.003	0.073	0.005	0.236	0.008
Apata	0.125	0.018	1.619	0.252	0.009	0.328	0.017	0.072	0.014	0.410	0.031
Waipapa	0.371	0.052	4.804	0.747	0.009	0.328	0.017	0.072	0.014	0.410	0.031
Waitao	0.733	0.202	7.797	1.124	0.018	0.306	0.008	0.164	0.027	0.487	0.035
Rocky	0.168	0.043	1.464	0.212	0.051	0.376	0.012	0.268	0.034	0.695	0.046
Waimapu	1.870	0.744	16.838	2.381	0.022	0.614	0.012	0.302	0.039	0.938	0.051
Waikareao	1.808	1.346	7.834	0.912	0.035	0.804	0.017	0.141	0.034	0.981	0.051
Te Rereatukahia SH2	0.294	0.104	2.169	0.319	0.006	0.158	0.005	0.079	0.008	0.243	0.013
Waitekohe SH2	0.294	0.104	2.169	0.319	0.005	0.040	0.005	0.090	0.008	0.135	0.013
SUM all rivers (whole harbour)	24.779	10.336	183.161	25.739	0.215	4.351	0.157	2.085	0.297	6.651	0.454

Table 10*: Average discharge and nutrient concentration of the timeseries used to force the biogeochemical model at each of the freshwater discharge points (for winter).*

	Winter										
River or stream ID	**Flows (m3/s)**				**Average Nutrient concentration (g/m3)**						
	Mean	**min**	**max**	**std dev**	**NH4**	**NO3**	**DRP (PO4)**	**DON**	**DOP**	**TN**	**TP**
Uretara	1.214	0.458	10.446	1.184	0.003	0.333	0.004	0.025	0.005	0.361	0.009
Tuapiro	2.274	0.656	27.137	3.182	0.004	0.144	0.006	0.042	0.008	0.189	0.014
Te Mania	0.585	0.209	5.359	0.617	0.009	0.421	0.005	0.060	0.012	0.490	0.017
Waiau	1.345	0.347	17.015	2.011	0.007	0.392	0.012	0.070	0.020	0.470	0.031
Wairoa	18.913	8.766	89.544	12.077	0.014	0.506	0.013	0.101	0.028	0.621	0.042
Te Puna	0.480	0.100	4.195	0.578	0.010	0.642	0.013	0.031	0.010	0.683	0.023
Wainui	0.604	0.126	5.279	0.727	0.004	0.425	0.003	0.036	0.005	0.465	0.009
Aongatete	2.998	0.836	34.225	4.004	0.004	0.425	0.003	0.036	0.005	0.465	0.009
Apata	0.213	0.044	1.859	0.256	0.010	0.642	0.013	0.031	0.010	0.683	0.023
Waipapa	0.631	0.132	5.516	0.760	0.010	0.642	0.013	0.031	0.010	0.683	0.023
Waitao	1.153	0.490	7.560	0.960	0.023	0.554	0.007	0.065	0.018	0.641	0.026
Rocky	0.270	0.136	1.422	0.175	0.203	0.876	0.014	0.301	0.049	1.380	0.063
Waimapu	2.759	1.356	16.336	2.034	0.019	0.919	0.012	0.077	0.022	1.015	0.034
Waikareao	2.072	1.600	7.466	0.810	0.154	1.027	0.015	0.149	0.037	1.329	0.052
Te Rereatukahia SH2	0.585	0.209	5.359	0.617	0.004	0.467	0.006	0.040	0.006	0.510	0.012
Waitekohe SH2	0.585	0.209	5.359	0.617	0.005	0.252	0.005	0.039	0.006	0.296	0.011
SUM all rivers (whole harbour)	36.682	15.678	244.077	30.607	0.480	8.667	0.144	1.134	0.252	10.281	0.396

4.1.2 Comparison to Monitoring data

Salinity variations in the hydrodynamic model were not calibrated because the monitoring stations were not measured at sufficient resolution to conduct a detailed calibration. However, salinity surveys were compared against model output. Because it was very difficult to collect salinity surveys at a consistent time of the tide, the observations were plotted against the mean and standard deviation over a day for the same day as each observation was made

(Figure 9). Results show that modelled salinity generally compared well with observed salinity, with more salty conditions in summer than in winter (which reflects the lower freshwater discharge combined with increased evaporation). When the salinity was generally lower (which occurred during events), sometimes the mean was not well captured. However, the observations were nearly always within the range of model outputs for the day that the observation occurred. During storm events, the salinity varied considerably in the model as the freshwater discharge is advected around the harbour by the tide. Appendix 5 shows the model-data comparison for each site separately.

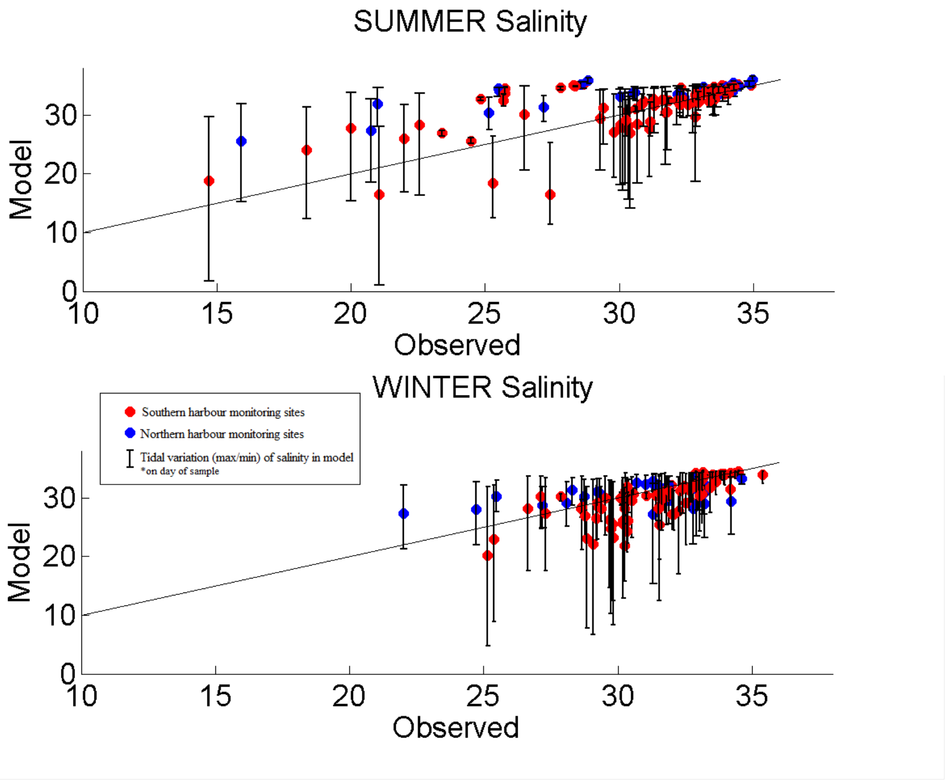

Figure 9*: Salinity observations compared to salinity model output over the period where the salinity surveys were conducted by the Bay of Plenty Regional Council. A site specific comparison is provided in Appendix 5.*

Flushing time is another parameter that is difficult to validate. It is also one of the single most important drivers of the biogeochemical model, in that biogeochemical processing can operate over longer time scales, and the longer water is retained in a region, the more chance there is for that processing to occur. In order to determine whether the flushing times predicted by the model were realistic, we compared them to flushing times from previous studies. Figure 10C shows the flushing time calculated by a study conducted using the ELCOM hydrodynamic model by Tay et al., (2013). The patterns are similar to those reported here, with flushing around the entrance being less than a day, reaching 7-8 days in the shallow central regions separating the north and south basin. The other way of addressing exchange is to measure geochemical tracers. Figure 10A and 10B shows the results of a tracer (Radium) which marks groundwater and freshwater in an estuary, and determines how long that has been in the estuary. The different isotopes of Radium track groundwater from different sources, and the isotope that likely represents shallow contributions shows that the water in the upper harbour region is approximately 6-8 days old, and gets old and older toward the entrance (the freshwater component of open ocean sea water is really old because the long travel time).

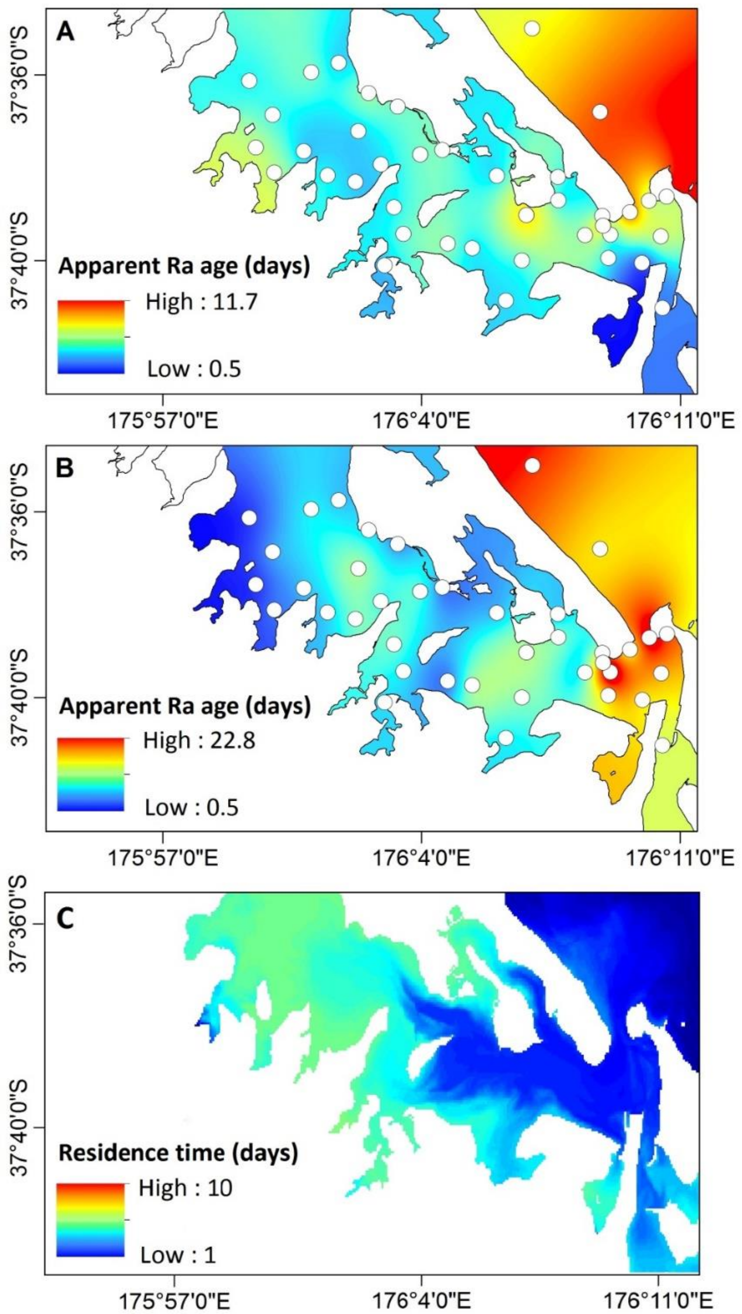

Figure 10*: The apparent Ra age of surface water in Tauranga Harbour using (A) the $^{224}Ra/^{223}Ra$ AR and (B) the $^{223}Ra/^{226}Ra$ AR compared with (C) a previous physical residence time model using numerical modelling (provided by Tay et al., 2013). Figure from Stewart (2021).*

Nutrient concentrations (like salinity) are also difficult to verify because they can have strong spatial gradients which are advected quickly past monitoring sites by the tide. They also change during the day, with processes such as uptake by algae, nitrification and denitrification which operate on smaller spatial scales. To compare the model output to observations, the model output was averaged for the day of the observations, and plotted as a mean plus standard deviation. Figures 11–14 show examples of the comparison (for Waikareao) and the remaining sites are shown in Appendix 3. At Waikareao, the model reproduced *DIN*, NO_3^-, *TN*, *DON* and PO_4^{3-} concentrations fairly well, but struggled with NH_4^+ and *Chl-a* in summer, which may be because the temperature is not modelled, but set to a constant value for summer and another constant value for winter. Entrance conditions were represented more consistently (which was probably because the entrance receives water from a wide range of sources, so observations and model output at this site represent more of a regionally-integrated view of conditions). Table 11 shows a qualitative assessment of model performance. Most components were reasonably well modelled at most sites, with the exception of ammonium which is always too low in the model. This could be potentially be adjusted by increasing the ammonium uptake rate in the algae model, while also increasing the mortality to maintain the algal levels approximately the same. Ammonium is also very sensitive to the sediment denitrification rate (see the next section).

***Table 11**: Qualitative assessment of biogeochemical model performance (Figures 11–14 and Appendix 3), with blue indicating that the modelled value is always too low, and red indicating that the modelled value is always too high. S = summer, W = winter.*

	Chl-a		DON		DOP		DIN		NO_3		NH_4		PO_4		TN		TP		S	
	S	W	S	W	S	W	S	W	S	W	S	W	S	W	S	W	S	W	S	W
Entrance																				
Waikareao																				
Tollbridge																				
Tilby Point																				
Omokoroa																				
Kauri Point																				
Tanners Point																				

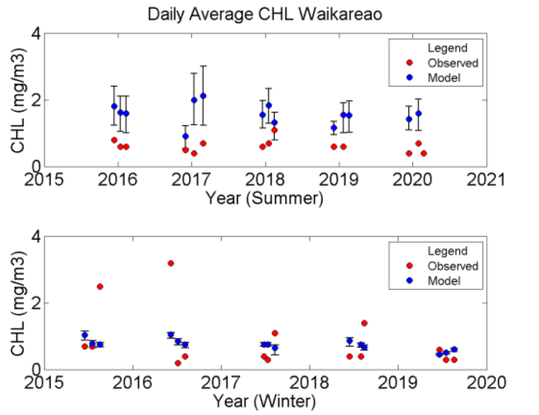

***Figure 11**: Observed and modelled Chl-a concentration for Waikareao monitoring site. Error bars represent variability over a day and the blue points represent the mean over a day.*

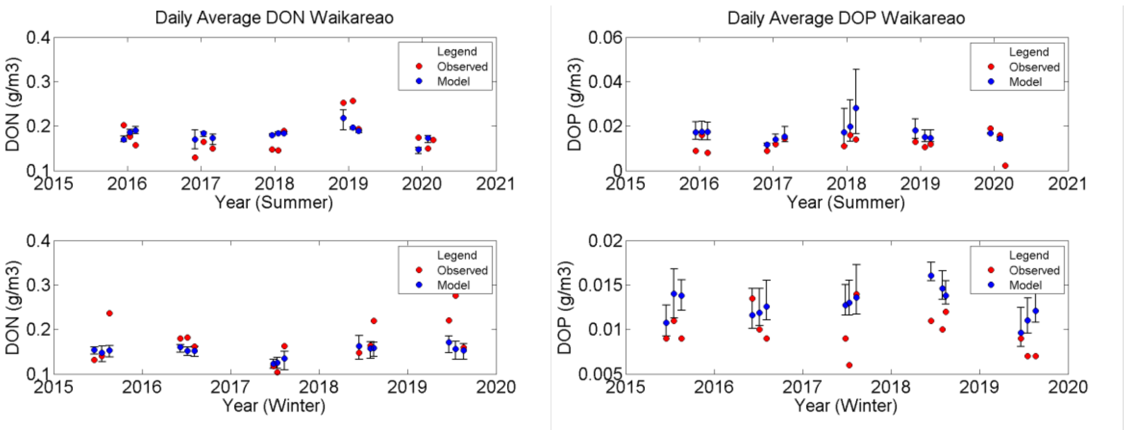

***Figure 12**: Observed and modelled DON and DOP concentrations for Waikareao monitoring site. Error bars represent variability over a day and the blue points represent the mean over a day.*

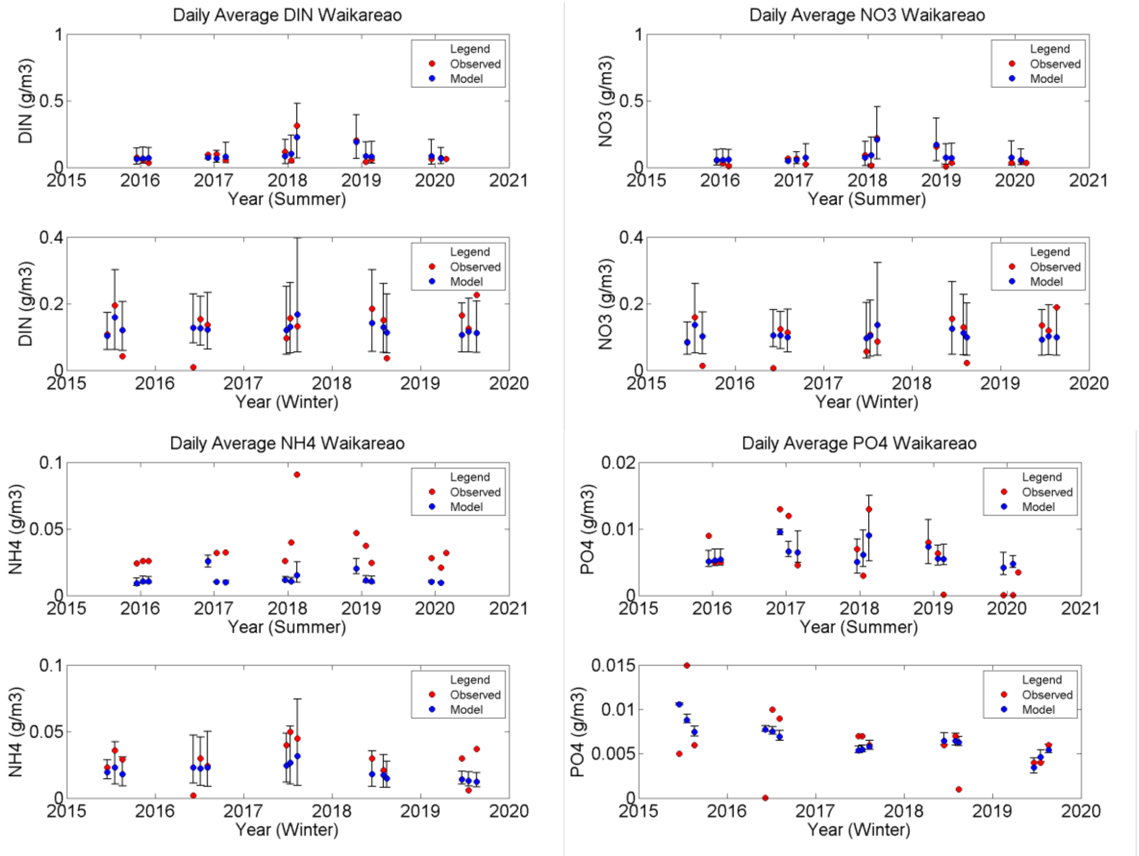

***Figure 13**: Observed and modelled DIN, NO_3^-, NH_4^+ and PO_4^{3-} concentrations for Waikareao monitoring site. Error bars represent variability over a day and the blue points represent the mean over a day.*

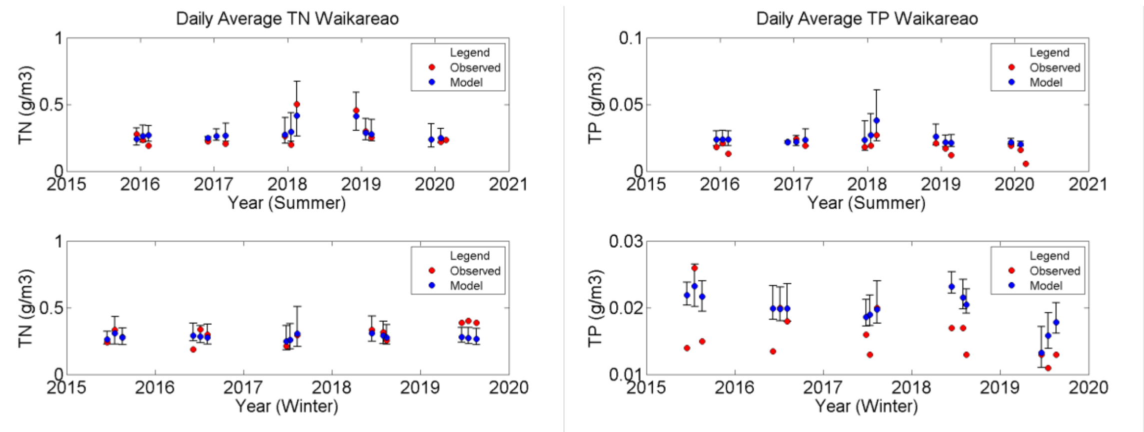

***Figure 14**: Observed and modelled TN and TP concentrations for Waikareao monitoring site. Error bars represent variability over a day and the blue points represent the mean over a day.*

4.1.3 Sensitivity analysis

The number of parameters needed for the biogeochemical model is very large, and the main reason why we took a simple approach and only modelled one algal group. The implication for this is that effect all higher trophic levels are subsumed into the mortality rate in the algal model. To tune the model so that it better reflected conditions at the monitoring site, we did a sensitivity analysis, and increased/decreased a subset of key parameters by 10%. This exercise showed that the model is very sensitive to the denitrification rates in the sediments, and productivity rates to a lesser extent. The sensitivity is regionally dependant. The significance of this (apart from providing insight into the best way to tune the model), is to show that reducing loading at boundaries is not the only way to reduce loading within regions, that if denitrification rates could be improved by improved sediment composition (sandier sediments have generally greater denitrification capacity), that might also contribute to improving attribute states within regions. Given the importance of sediment denitrification, if the biogeochemical models were to be made more complex, the next component would be to add a benthic algal group rather than to add more trophic levels to the water column processes.

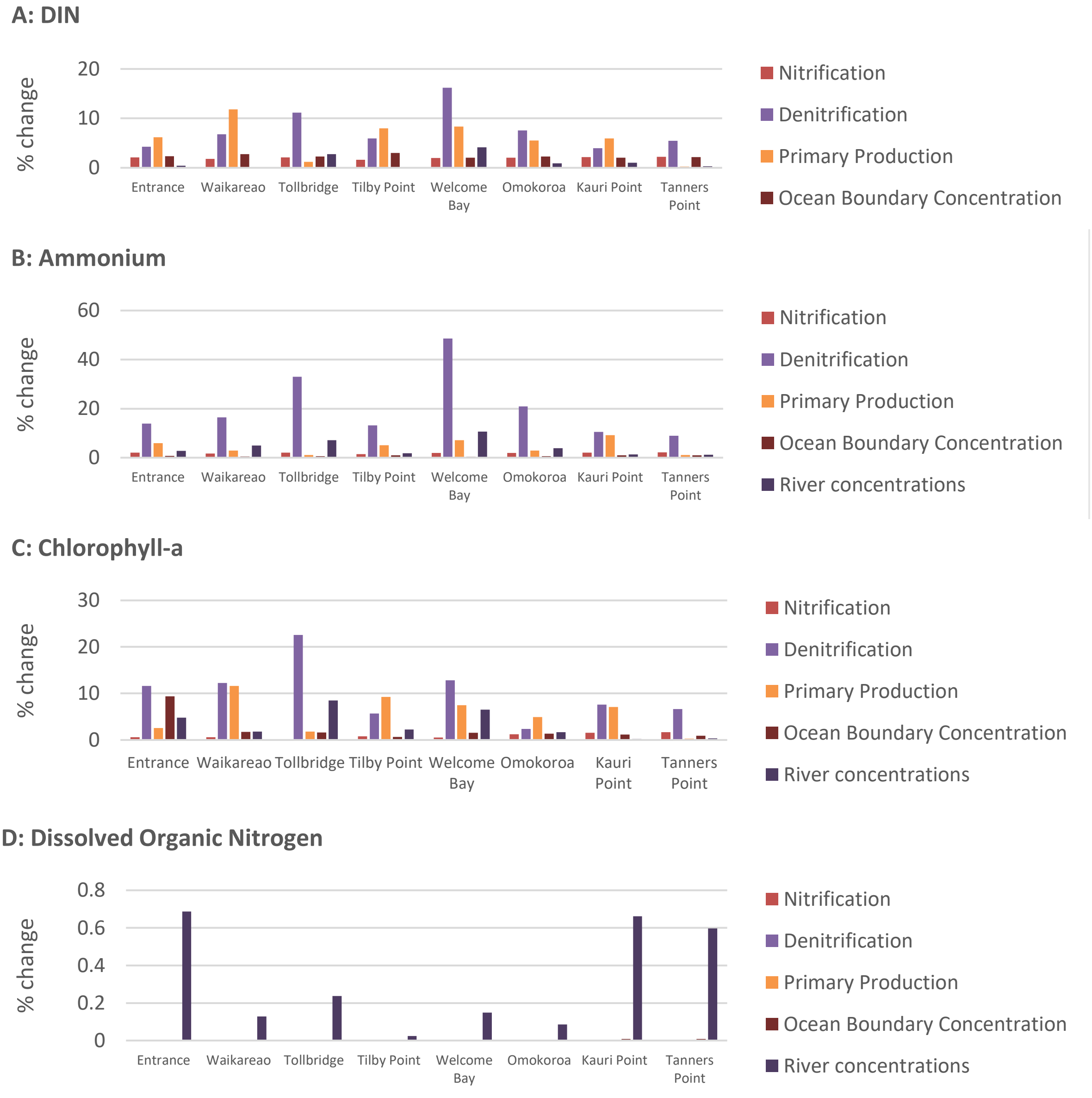

Figure 15: *Sensitivity of 4 key model parameters at the council monitoring sites when model settings are changed by ±10%. Change is quantified as the maximum minus the minimum value normalised by the average.*

4.1.4 Source-Sink Analysis

One of the more powerful tools associated with the DELWAQ modelling environment is the ability to analyse the sources and sinks of a particular fraction in multiple defined regions. To do this, we defined areas that were consistent with the briefing regions provided by BoPRC (Table 1). The output of this analysis is to list the sources and sinks from: each defined region, sediment denitrification, water column processes (nitrification and uptake), freshwater discharge and change in storage within that region, all of these for each of the modelled parameters. We present this information in two ways, one is to sum all the transfers from and to for each region, sum the sources and sinks to provide the net transfers and graph the 5 grouped components and presented them on a map. This information (NO_3 + NH_4) is shown in Figures 16 and 17. The other is to break the net sources and sinks into regions, so that it is possible to track DIN at a site to a particular region (Tables 12 and 13). Tables 12 and 13 are also graphically presented in a series of Figures in Appendix 6.

In principle, regions that contain freshwater discharges create a net source (+) of DIN to that region. Regions that are shallow and intertidal, tend to have net sinks from denitrification, for example regions 9, 7, 27 and 28. The region directly fed by the Wairoa River (region 3) shows that the net source from the river is directly balanced by a transfer to the adjacent region, indicating that strong flows here cause material to get advected toward the entrance quickly. In the many shallow areas with little freshwater input, sources from exchange from the main central are generally balanced by uptake by algae and denitrification. The central north harbour is odd because it appears that exchange is unbalanced. We have looked into this, and the exchange values are so large that the balance between them is close to the precision of the model. The key point here is that these regions are dominated by exchange. Differences in patterns between winter and summer are not strong, mainly being that the discharge contribution increases in winter.

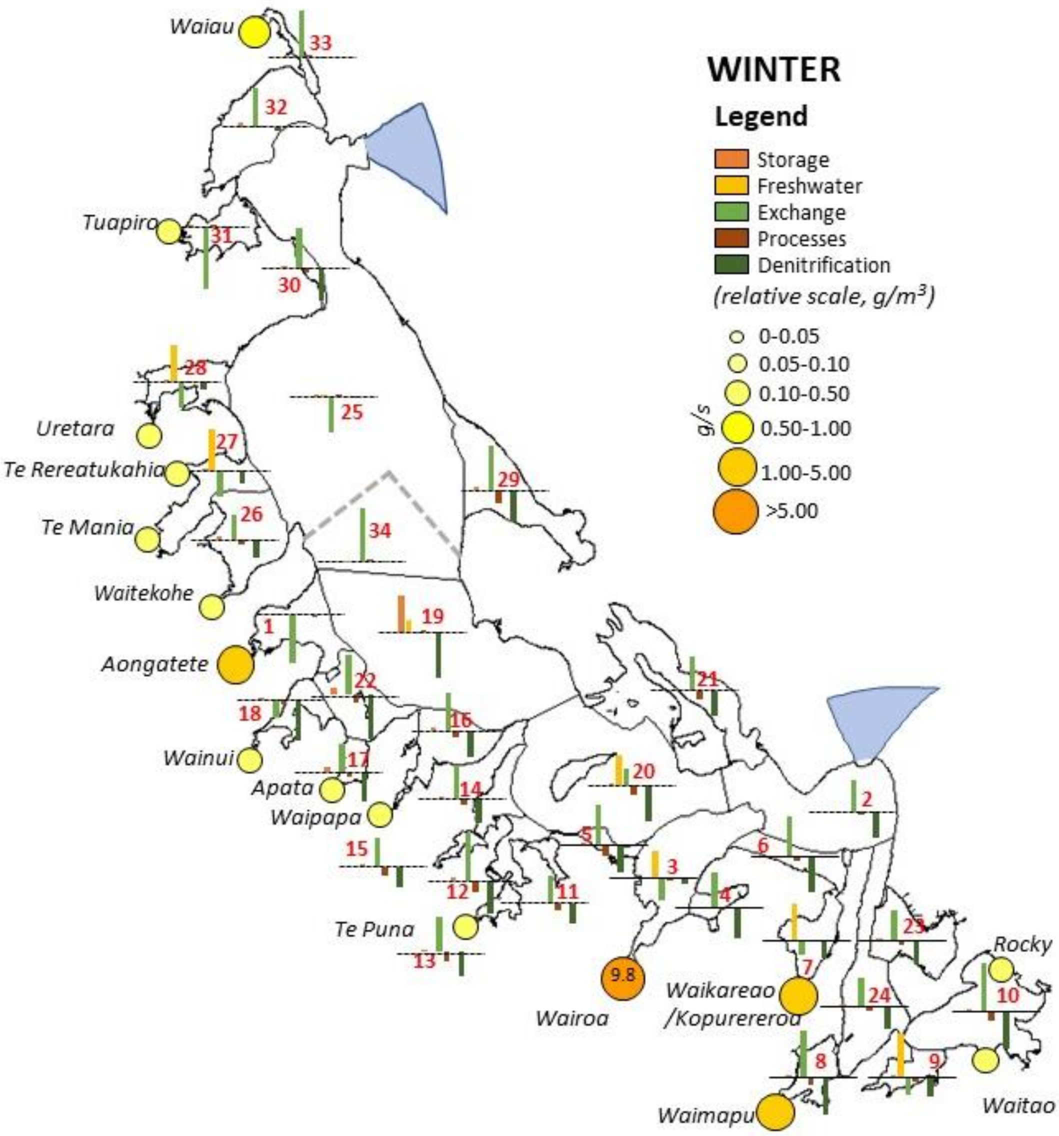

***Figure 16**: Overview of the net contribution of sources versus sinks of NO_3 + NH_4 in each region of the harbour (for average of 5 years of winter runs). Scales are in g/m^3 and reflect relative differences between sites. Within the central north harbour waters, exchange is the difference between a very large negative and very large positive number, which means that the exchange calculation may be affected by the precision of the model. Storage is the net changes in each region over the whole modelling time period. In many places, the amount gained from exchange with a different region or from a freshwater source is balanced by denitrification and algal uptake. The coloured circles represent the average freshwater loading.*

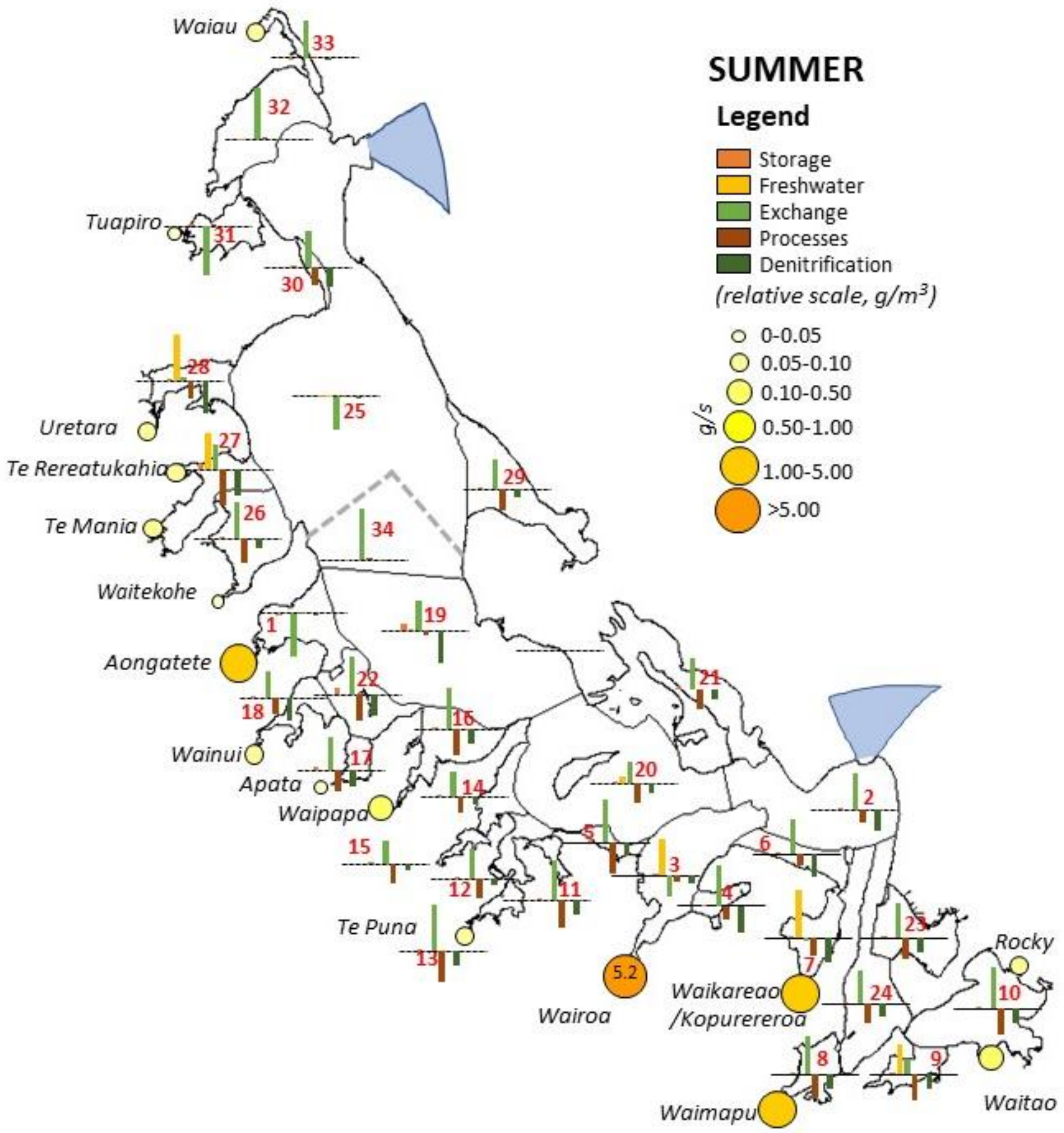

Figure 17*: Overview of the net contribution of sources versus sinks of NO_3 + NH_4 in each region of the harbour (for average of 5 years of summer runs). Scales are in g/m^3 and reflect relative differences between sites. Within the central north harbour waters, exchange is the difference between a very large negative and very large positive number, which means that the exchange calculation may be affected by the precision of the model. Storage is the net changes in each region over the whole modelling time period. In many places, the amount gained from exchange with a different region or from a freshwater source is balanced by denitrification and algal uptake. The coloured circles represent the average freshwater loading.*

It is also interesting to examine which region is most affected by other regions. These are presented as a net exchange, and so some immediately adjacent areas (for example region 25 is much closer to region 1 than is region 34) do not register as being important. This is because water is only exchanged across this region. For example, DIN in region 1 comes from region 32, 33, 34 and 19, but travels straight through region 25 on the way from 32 and 33. Similarly, Wairoa River region water (region 3) does not end up in region 2 (the entrance), but rather in area 20. In area 2, nitrogen simply transitions into the open ocean. The categories “other” represent regions not included in any defined area.

Areas identified as being the most susceptible to macroalgal blooms (C and D grade) by the Estuarine Trophic Index (Table 1) include Ongare (region 30), Ōtumoetai (region 6), and Lower Estuary (region 2). None of these regions have direct freshwater inflows, but are influenced by other regions in the harbour. For example, Ōtumoetai has sources of DIN from Wairoa and the southern estuaries (Figure A48), and also high rates of denitrification (Tables 14 and 15 and Figures 16 and 18) because it is a shallow intertidal region. Ongare has main sources from the Wainui – Waipapa areas (17, 18, 22, 34, Figure A48) which are brought past the Ongare site on as the tide drains out of the northern basin. The lower estuary (region 2), is the receiving environment of water from Wairoa (3,4), Ōtumoetai (6) and Waikareao (7) regions (Figure A48), but has some contribution from denitrification reducing DIN probably because of the extensive shallow centre bank region. Although regions in proximity to higher freshwater loading (Wairoa (3), Waikareao (7), Waimapu (9)) are generally shown to be heavily influenced by that loading, there are exceptions. In the Aongatete (1) region, the loading is quickly transferred to surrounding regions. Even though there is quite high loading from Wairoa (3), the influence on the proximal region is similar to Waikareao, and that is because the strong exchange in the Wairoa region quickly transfers the DIN to surrounding sites.

Estuaries identified in Table 1 as being in poor trophic state were Rereatukahia Estuary (27) Southern Estuary (24), Te Puna Estuary (12,13), Uretara Estuary (28), Waikaraka Estuary (11), Outer Wainui (22), Waipapa (16), in addition to Ongare described above. Te Puna receives DIN from surrounding regions and the main central harbour (regions 20, 21, 2, shown in Figure A46 and A52). Similarly, Waikaraka receives DIN for a wide range of sources, including the northern basin (but mostly surrounding regions) (Figure A50). Waipapa receives DIN from the northern harbour (Figure A52). The Southern Estuary exchanges nutrients with all surrounding regions, and also Ōtumoetai and Waikareao (Figure A53). Although the Southern Estuary does not have large freshwater sources in surrounding regions, these freshwater sources have relative high concentrations making the loading high (Figure 16 and 17), and also the Wairoa and Waikaraeo contribute either directly or indirectly through exchanges with regions 2 (Lower Estuary) and 6 (Ōtumoetai). In general, results from the modelling are more similar to the outcomes of Tool 1 than of Tool 2 of the ETI. However, there are a few exceptions. Places like Rangataua Bay (10) are ranked in a good state by the ETI (probably because they are very intertidal), whereas the modelling here indicates that they are well over the threshold for class B (likely because they exchange all their water with areas in a lower state).

***Table 12**: Source to sink analysis for DIN (=NO_3^-+NH_4^+) for all summer runs. Each area of interest (locations shown in Appendix 1) is listed at the top, then each row shows the amount of discharge into each of those regions from freshwater sources (labelled as "discharge"), the contribution of exchange from sources not included in any of the regions of interest ("other"), the net contribution of each region ("location of main sources"), the uptake by water column processes ("processes") and water column nitrification ("nitrification"), and finally the removal by sediment denitrification ("denitrification"). All numbers are in g/m^3.*

	Area of Interest																																	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
Storage	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Discharge	0	0	2	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0
Other	0	1	0	-13	0	-2	-1	-1	-2	1	1	-1	0	0	0	0	0	1	0	0	1	1	0	1	0	-1	0	-2	0	3	0	0	0	0
Location of main sources																																		
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-2	0	-2	0	0	0	0	0	0	0	-1	-1	0	0	-1	0	-2	0
2	0	0	0	21	0	1	-8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	1	-2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	-2	0	0	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	-6	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	3	0	0	0	-8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	-1	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
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13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-2	0	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-2	0	0	0	0	0	0	0	0
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18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	11	0	-7	0	0	0	0
19	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	-8	42	0	0	-1	-3	0	0	0	2	6	-2	0	-1	0	0	0	0
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21	0	0	0	-1	0	0	0	0	0	0	-2	-1	0	5	2	0	0	0	0	0	0	0	0	0	0	-3	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7	-26	0	0	0	0	0	0	0	0	-1	-10	0	5	0	0	0	0
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24	0	0	0	0	0	10	4	5	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0
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26	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	-4	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0
29	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0
31	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
32	-4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	-2	0	1	1
33	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
34	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	-1	0	9	2	-1	3	0
Processes	0.00	-0.75	-0.38	-0.55	-0.29	-1.61	-0.70	-0.33	-0.26	-0.25	-0.34	-0.20	-0.29	-0.15	-0.18	-0.10	-0.06	-0.31	0.00	-0.18	-0.20	-0.10	-0.39	-0.38	0.00	-0.14	-0.07	-0.65	-0.21	-0.26	0.00	0.00	0.00	0.00
Nitrificatio	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Denitrificat	0.00	-1.24	-0.48	-1.00	-0.13	-3.31	-0.98	-0.21	-0.15	-0.14	-0.17	-0.08	-0.14	-0.07	-0.06	-0.05	-0.05	-0.45	-0.01	-0.10	-0.09	-0.08	-0.28	-0.26	-0.01	-0.06	-0.05	-1.22	-0.08	-0.28	-0.01	0.00	0.00	0.00

Table 13: *Source to sink analysis for DIN (=NO_3^-+NH_4^+) for all winter runs. Each area of interest (locations shown in Appendix 1) is listed at the top, then each row shows the amount of discharge into each of those regions from freshwater sources (labelled as "discharge"), the contribution of exchange from sources not included in any of the regions of interest ("other"), the net contribution of each region ("location of main sources"), the uptake by water column processes ("processes") and water column nitrification ("nitrification"), and finally the removal by sediment denitrification ("denitrification"). All numbers are in g/m^3.*

		Area of Interest																																
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
Storage		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Discharge		0	0	10	0	0	0	7	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	13	0	0	0	0	0	0
Other		0	7	-1	-76	-1	-3	-4	-5	-5	3	3	-1	2	0	0	-1	0	2	0	0	2	3	0	2	0	-2	0	-5	0	7	0	0	0	0
Location of main sources	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-5	0	-2	0	0	-1	0	0	0	0	-2	-1	0	0	-1	0	-2	0
	2	0	0	1	128	1	-28	-29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	3	0	-2	0	1	5	-8	-1	0	0	0	2	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	4	0	-11	0	0	0	47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	5	0	0	-1	0	0	0	0	0	0	0	3	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	6	0	2	0	-42	0	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0
	7	0	12	0	0	0	-33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-2	-2	0	0	0	0	0	0	0	0	0	0
	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	-4	0	0	0	0	0	0	0	0	0	0
	9	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	10	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0
	11	0	0	0	0	-1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	12	0	0	0	0	0	0	0	0	0	0	-2	0	0	-1	2	0	0	0	0	-1	1	0	0	0	0	0	0	0	-1	0	0	0	0	0
	13	0	0	0	0	-1	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	14	0	0	0	0	0	0	0	0	0	0	0	1	0	0	5	0	0	0	0	1	-7	0	0	0	0	2	0	0	0	0	0	0	0	0
	15	0	0	0	0	0	0	0	0	0	0	0	-1	0	-1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-8	0	0	0	0	0	0	0	0
	17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-6	0	0	0	0	-9	0	0	0	0	0	0	0
	18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	29	0	-15	0	0	0	0
	19	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	-13	81	0	0	-4	-5	0	0	0	5	17	-9	0	-3	0	0	0	0
	20	0	0	-8	-3	1	-4	0	0	0	0	12	9	13	-10	1	0	0	0	0	0	2	0	0	0	0	3	0	0	0	0	0	0	0	0
	21	0	-1	1	-3	-2	0	0	0	0	0	-10	-6	-16	17	5	0	0	0	0	-1	0	0	0	0	0	-7	0	0	1	0	0	0	0	0
	22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	14	-50	0	0	0	0	0	0	0	0	-2	-35	0	12	0	0	0	0
	23	0	0	0	0	0	0	9	-8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
	24	0	0	0	0	0	43	16	14	0	-2	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0
	25	0	0	0	0	0	0	0	0	0	0	-3	-1	0	-3	1	-6	3	-44	0	0	3	5	0	0	0	7	-6	16	0	-17	0	0	0	0
	26	0	0	0	0	0	0	0	0	0	0	0	-1	0	-2	-13	2	0	0	0	-1	2	0	0	0	0	0	0	0	0	0	0	0	0	0
	27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
	28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	-2	0	0	0	0
	29	0	0	0	0	0	0	0	0	0	0	-2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	0	0	0	-1	0	0	0	0	0	-3	0	0	0	0	0	0
	31	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0
	32	-4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	-2	0	1	1
	33	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	34	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	-2	0	18	2	-1	3	0
Processes		0.00	-0.52	-0.31	-0.40	-0.20	-1.06	-0.38	-0.14	-0.08	-0.08	-0.26	-0.12	-0.25	-0.07	-0.09	-0.04	-0.02	-0.12	0.00	-0.09	-0.12	-0.03	-0.17	-0.16	0.00	-0.06	-0.02	-0.29	-0.12	-0.10	0.00	0.00	0.00	0.00
Nitrificatio		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Denitrificat		-0.01	-4.92	-1.87	-4.21	-0.51	-12.93	-3.48	-0.69	-0.38	-0.35	-0.75	-0.31	-0.67	-0.23	-0.19	-0.15	-0.11	-1.16	-0.01	-0.34	-0.35	-0.17	-0.90	-0.82	-0.01	-0.17	-0.12	-3.06	-0.29	-0.63	-0.01	0.00	0.00	0.00

4.2 Loading Scenarios

Loading reduction scenarios were undertaken by reducing the concentration at the discharge points by 20% and 40%, and running the biogeochemical model for all 10 of the 3-month time periods (winter and summer for 2015-2020). The results are presented as spatial maps of nitrate, ammonium, phosphate and total nitrogen for winter (Figure 18) and summer (Figure 19). These results are also presented as a Table (Table 16 and 17), as spatial maps of percentage reduction (Figure 20) and as tables of percentage reduction at each of the monitoring sites (Table 16). Finally, these are presented as changes to the Estuarine Trophic Index Tool (ETI) scores in Figure 21. Note that in tables 16 and 17, a lot more sites are the C range than predicted by the ETI tool. However, quite a few are close to the threshold of 0.18 g/m3.

Given that the harbour is a well-mixed barrier enclosed estuary (or lagoon) with little freshwater input relative to tidal exchange, changes to river and stream loading did not have a large effect on harbour water quality, unless in immediate proximity to the discharge point. The large central areas, and the northeast side of the estuary were relatively less affected by changes to freshwater input. Conversely, in areas close the Wairoa River entrance (Tilby Point), the Waikaraeo Estuary and Welcome Bay (Waimapu), were strongly improved by reductions in nutrient loading, moving from total nitrogen category D, to category C (in Table 1). Some places like Uretara Estuary and Blue Gum Bay even moved into category B. Loading reductions did not result in any areas moving into category A. Reductions were generally more effective in the southern basin compared to the northern basin, which is probably more an indication that there is simply more loading in the southern basin (so a % reduction is a greater absolute reduction), rather than because of the physiographic differences (in fact the southern basin is generally better flushed because of the deeper entrance and greater freshwater input). In general loading reductions improved conditions in the shallow sub-estuaries more than in the main harbour, which is probably due to two effects: firstly, the volume of water is smaller in the sub-estuaries, and secondly, denitrification is more effective in shallow small estuaries. Loading reductions were much more effective in winter than in summer, which is a reflection that loading is driven partially by discharge, which is higher in winter.

The regions with high current macroalgal bloom susceptibility (Ongare (30), Ōtumoetai (6), Lower Estuary (2)) were all graded in category C (moderately impacted), and neither of the loading reduction scenarios resulted in a change to the overall TN grade. These sites are all sites that are well away from the source of freshwater loading, and receive water for a large range of sources. Ongare receives DIN directly from nearly all the subestuaries in the North Harbour, and the rest indirectly through the central exchange region (Figure A48). Likewise, regions 2 and 6 are directly influenced by all the surrounding regions (Figure A48), and in turn, those regions are directly influenced by the Wairoa, the Kopurereroa and the Waimapu sources. The source/sink analysis was run over 3-month periods for 5 years, and then averaged. In most areas, nutrients sourced from exchange from surround regions were used up by denitrification (which is always a sink) and uptake from water column processes (the brown and dark green bars in Figures 16 and 17 are generally negative, and match the yellow discharge and light green exchange bars. There are very few areas in which storage changes significantly over 3 months.

A consequence of the degree of exchange that occurs within the harbour means that it takes a long time to change concentrations significantly within a region. When calculating a residence time of 1-8 days for a region, this calculation indicates how long it would take to replace the water in that region, with water from surrounding regions. If the surrounding regions had zero DIN concentration, the nutrient load would be reduced substantially and quickly (expediated by denitrification and water column processes). However, the difference between regions is very small, so when the nutrient loading is decreased in a region with high freshwater loading, it takes a long time for the surrounding regions to feel that effect (much longer than 8 days). The model used here also includes a large shelf region, in order to account for exchange with the near-shelf region, and so the nutrients would need to be mixed away from that region too. Port (2016) measured the ebb and flood DIN concentration weekly at Mount Entrance for two years, and although the ebbing tide had higher concentrations than the flooding tide, the difference was not large (his Figure 4.4 and 4.5).

We could think of the estuarine hydrodynamics causing an “attenuation” on the load reduction effect. So, if for example, a 40% loading reduction in the Wairoa River causes a 7% reduction of nitrate at the entrance, the reduction effect is attenuated by 80% in summer, whereas the reduction is only attenuated by 25% at Tilby Point which is close to the Wairoa discharge.

Reductions had most effect on nitrate, which is very mobile in the environment, whereas the effect on ammonium was much lower. Ammonium is preferentially used in biological uptake, and also transforms quickly into nitrate by nitrification. Both these reasons mean that changes to ammonium are less connected to changes to freshwater loading.

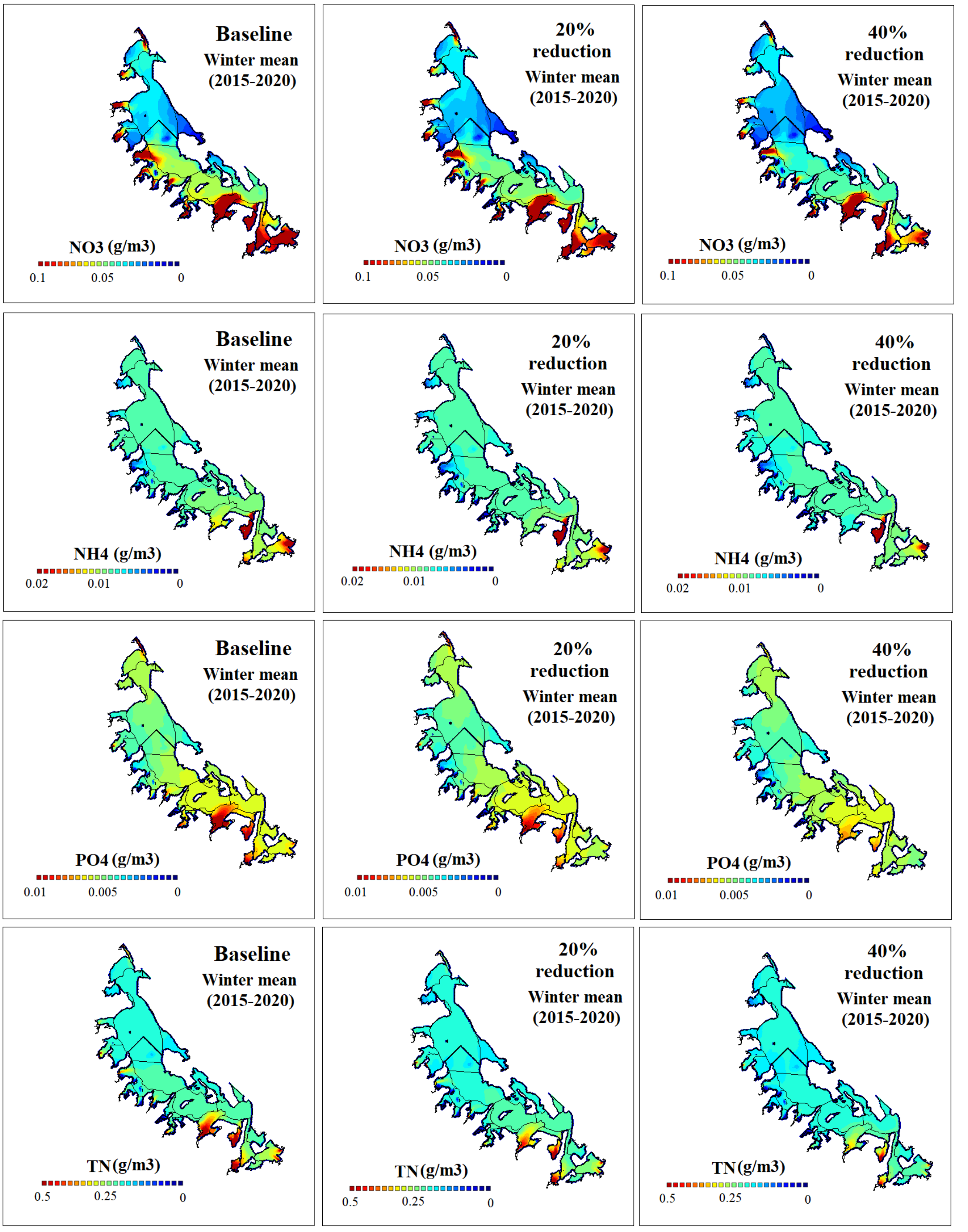

Figure 18*: Spatial maps of nitrate, ammonium, phosphate and total nitrogen concentrations (g/m^3) for each loading reduction scenario for winter.*

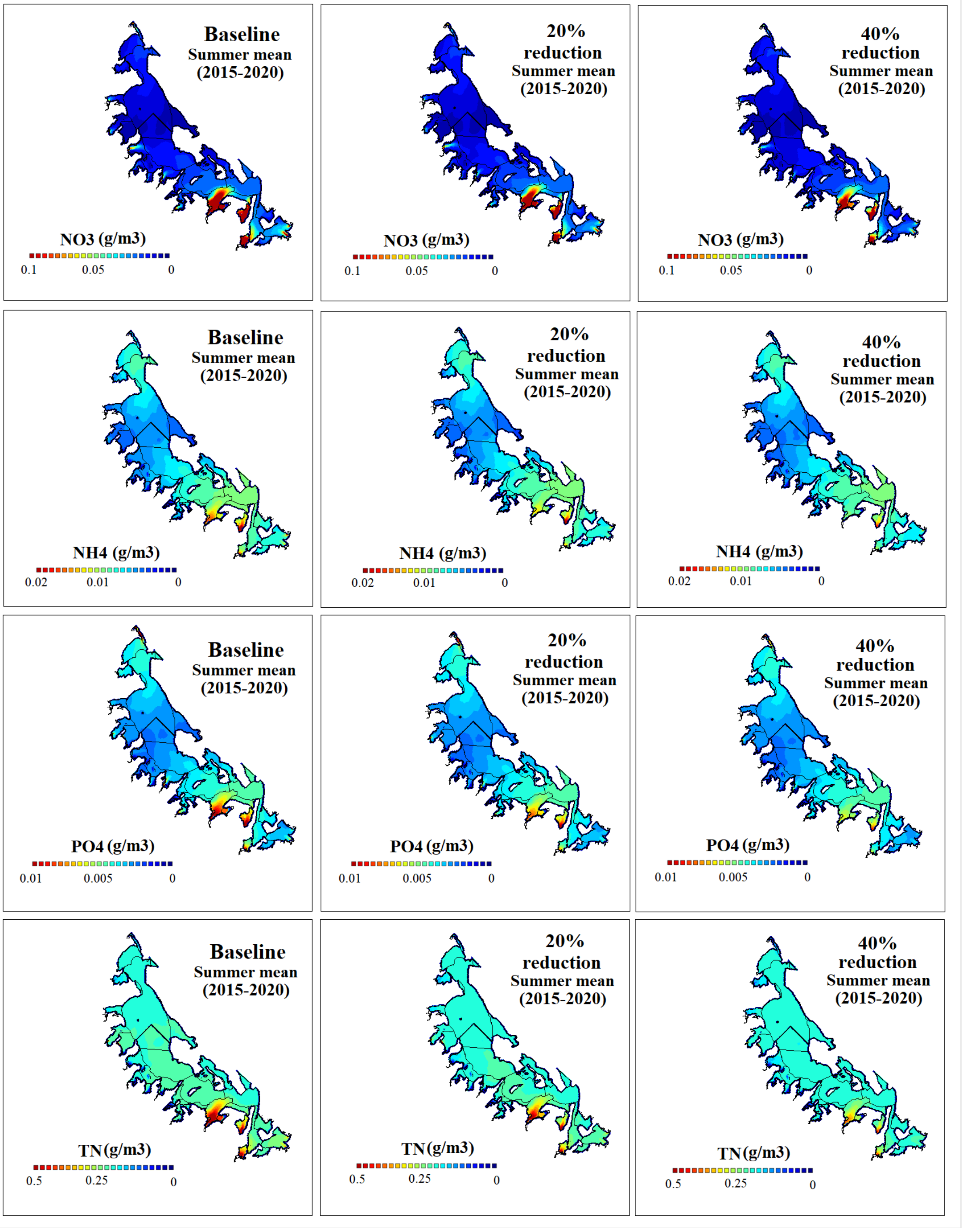

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Figure 19*: Spatial maps of nitrate, ammonium, phosphate and total nitrogen concentrations (g/m*^{3}*) for each loading reduction for summer.*

Table 14: *Concentrations of total nitrogen (TN) in each sub-region at baseline conditions and under each loading reduction scenario, for winter. The colour indicates the TN state band from Table 2. Note that the ETI tool 1 classification for Tauranga Harbour as a whole gave a class of B.*

		ETI Tool 1 (from Table 1)	ETI Tool 2 (Trophic State)	ETI Tool 2 (Macro-Algae)	BASELINE		20% reduction		40% reduction	
Region Name	**ID**				**Mean Winter TN (g/m³)**	**Standard deviation (g/m³)**	**Mean Winter TN (g/m3)**	**Standard deviation (g/m³)**	**Mean Winter TN (g/m³)**	**Standard deviation (g/m³)**
Aongatete	1	D	B	A	0.22	0.09	0.19	0.08	0.17	0.06
Hunters Creek	21	-	B	B	0.20	0.05	0.20	0.05	0.19	0.05
Lower Estuary	2	-	B	C	0.23	0.03	0.23	0.03	0.22	0.03
Mangawhai Estuary 1	14	A	B	A	0.21	0.04	0.21	0.04	0.20	0.04
Mangawhai Estuary 2	15	A	B	A	0.03	0.02	0.02	0.02	0.02	0.02
Otumoetai	6	-	B	C	0.26	0.05	0.24	0.05	0.23	0.04
Rangataua Bay	10	B	B	A	0.29	0.08	0.26	0.07	0.23	0.06
Southern Estuary	24	-	C	B	0.27	0.07	0.25	0.06	0.23	0.06
Te Puna Beach	5	-	B	B	0.23	0.03	0.23	0.03	0.22	0.03
Te Puna Estuary 1	12	C	C	A	0.22	0.05	0.21	0.05	0.20	0.05
Te Puna Estuary 2	13	C	C	A	0.27	0.13	0.24	0.11	0.20	0.08
Waikareao	7	D	B	A	0.50	0.23	0.42	0.18	0.35	0.13
Waikaraka Estuary	11	D	C	B	0.15	0.09	0.15	0.08	0.14	0.08
Waimapu Estuary	8	D	B	A	0.49	0.18	0.41	0.15	0.33	0.11
Wainui Estuary 1 (Outer)	22	-	C	A	0.21	0.04	0.20	0.04	0.19	0.04
Wainui Estuary 2	17	D	B	A	0.18	0.11	0.16	0.09	0.15	0.08
Apata (Wainui Estuary 3)	18	D	B	A	0.18	0.09	0.16	0.08	0.15	0.07
Waipapa Estuary	16	B	C	A	0.24	0.07	0.22	0.06	0.21	0.05
Waipu Bay	23	A	B	B	0.23	0.05	0.22	0.05	0.21	0.04
Wairoa 1	3	C	B	A	0.37	0.10	0.32	0.07	0.27	0.05
Wairoa 2	4	C	B	A	0.33	0.14	0.27	0.12	0.21	0.09
Welcome Bay	9	C	B	A	0.23	0.08	0.21	0.07	0.19	0.07
Middle Estuary	20	-	A	A	0.23	0.03	0.23	0.02	0.22	0.02
Upper Estuary	19	-	B	A	0.23	0.01	0.22	0.01	0.21	0.01
North Domain	25	-	B	B	0.21	0.02	0.21	0.02	0.20	0.02
Matahui West	26	-	B	A	0.40	8.80	0.35	7.05	0.30	5.30
Rereatukahia Estuary	27	B	C	A	0.27	1.32	0.25	1.06	0.22	0.79
Uretara Estuary	28	C	C	A	0.21	0.06	0.19	0.05	0.18	0.04
Blue Gum Bay	29	-	B	A	0.19	0.04	0.18	0.04	0.18	0.04
Ongare	30	-	C	D	0.21	0.05	0.20	0.05	0.20	0.05
Tuapiro Estuary	31	B	C	A	0.17	0.05	0.16	0.05	0.15	0.05
Tuapiro Athenree	32	-	B	A	0.20	0.03	0.20	0.03	0.20	0.03
Waiau Estuary	33	D	A	A	0.30	0.11	0.25	0.09	0.20	0.06
Central (Part of Northern)	34	-	B	B	0.20	0.03	0.20	0.03	0.19	0.03

Table 15: *Concentrations of total nitrogen (TN) in each sub-region at baseline conditions and under each loading reduction scenario, for summer*

Region Name	ID	ETI Tool 1 (from Table 1)	ETI Tool 2 (Trophic State)	ETI Tool 2 (Macro-Algae)	Mean Summer TN (g/m³)	Std deviation	Mean Summer TN (g/m³)	Std deviation	Mean Summer TN (g/m³)	Std deviation
Aongatete	1	D	B	A	0.19	0.05	0.18	0.05	0.17	0.05
Hunters Creek	21	-	B	B	0.22	0.02	0.21	0.02	0.21	0.02
Lower Estuary	2	-	B	C	0.22	0.01	0.22	0.00	0.22	0.00
Mangawhai Estuary 1	14	A	B	A	0.22	0.03	0.21	0.03	0.21	0.02
Mangawhai Estuary 2	15	A	B	A	0.05	0.03	0.05	0.03	0.05	0.03
Otumoetai	6	-	B	C	0.25	0.02	0.24	0.01	0.23	0.01
Rangataua Bay	10	B	B	A	0.26	0.02	0.24	0.02	0.22	0.01
Southern Estuary	24	-	C	B	0.25	0.02	0.24	0.02	0.23	0.01
Te Puna Beach	5	-	B	B	0.23	0.00	0.23	0.00	0.22	0.00
Te Puna Estuary 1	12	C	C	A	0.22	0.04	0.21	0.04	0.20	0.04
Te Puna Estuary 2	13	C	C	A	0.21	0.07	0.20	0.06	0.18	0.06
Waikareao	7	D	B	A	0.36	0.14	0.32	0.10	0.27	0.07
Waikaraka Estuary	11	D	C	B	0.17	0.08	0.16	0.08	0.16	0.08
Waimapu Estuary	8	D	B	A	0.40	0.09	0.35	0.07	0.29	0.05
Wainui Estuary 1 (Outer)	22	-	C	A	0.21	0.03	0.21	0.03	0.20	0.03
Wainui Estuary 2	17	D	B	A	0.18	0.08	0.17	0.07	0.16	0.07
Apata (Wainui Estuary 3)	18	D	B	A	0.18	0.07	0.17	0.07	0.16	0.06
Waipapa Estuary	16	B	C	A	0.22	0.04	0.21	0.04	0.21	0.04
Waipu Bay	23	A	B	B	0.23	0.01	0.22	0.01	0.22	0.01
Wairoa 1	3	C	B	A	0.38	0.12	0.33	0.09	0.28	0.05
Wairoa 2	4	C	B	A	0.37	0.14	0.31	0.12	0.24	0.09
Welcome Bay	9	C	B	A	0.23	0.05	0.22	0.04	0.21	0.04
Middle Estuary	20	-	A	A	0.23	0.00	0.23	0.00	0.22	0.00
Upper Estuary	19	-	B	A	0.23	0.01	0.22	0.01	0.22	0.01
North Domain	25	-	B	B	0.22	0.00	0.22	0.00	0.22	0.00
Matahui West	26	-	B	A	0.25	0.24	0.24	0.19	0.23	0.14
Rereatukahia Estuary	27	B	C	A	0.24	0.38	0.23	0.31	0.22	0.23
Uretara Estuary	28	C	C	A	0.20	0.02	0.20	0.02	0.19	0.02
Blue Gum Bay	29	-	B	A	0.22	0.01	0.22	0.01	0.22	0.01
Ongare	30	-	C	D	0.22	0.00	0.22	0.00	0.21	0.00
Tuapiro Estuary	31	B	C	A	0.18	0.04	0.17	0.04	0.17	0.04
Tuapiro Athenree	32	-	B	A	0.21	0.02	0.21	0.02	0.20	0.02
Waiau Estuary	33	D	A	A	0.18	0.04	0.16	0.04	0.14	0.04
Central (Part of Northern)	34	-	B	B	0.22	0.00	0.22	0.00	0.22	0.00

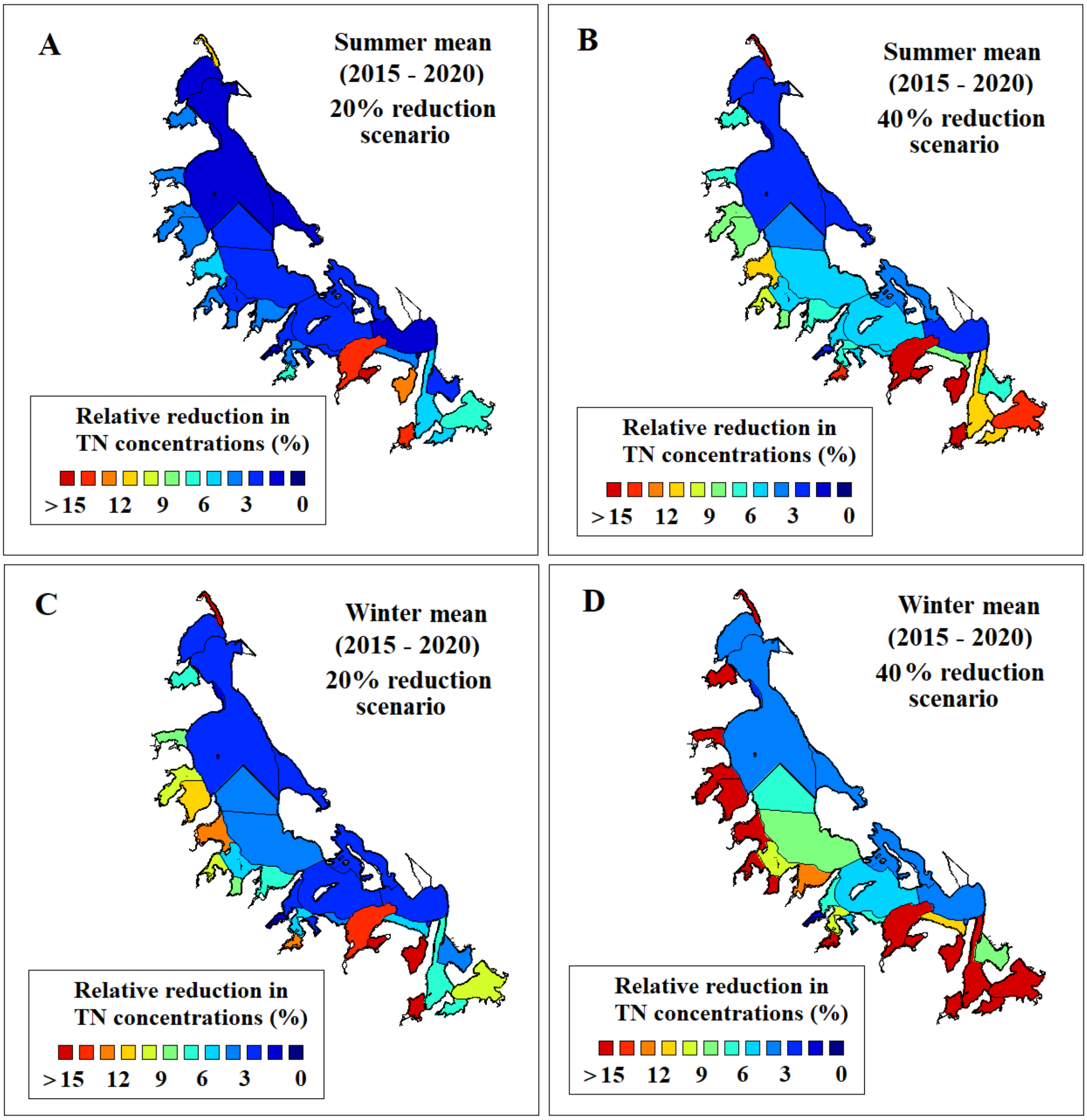

Figure 20: *Summary of reduction scenarios at monitoring points for the Reduction Scenarios 1 and 2 for winter (These are plotted as changes to the ETI score in Figure 21).*

Table 16: *Effect of changes to river loading on water quality at monitoring sites (data shown in Figures 18 and 19) for winter scenarios. Colour indicates magnitude of change.*

Monitoring Site	Site ID	NO_3 (%)		NH_4 (%)		PO_4 (%)		TN (%)		ALGAE (%)	
		-20%	-40%	-20%	-40%	-20%	-40%	-20%	-40%	-20%	-40%
Entrance	CQ947053	3.47	6.94	0.93	1.88	0.85	1.69	1.00	2.00	0.56	1.14
Omokoroa	EP020617	10.33	20.63	2.46	5.12	3.49	6.96	3.43	6.87	1.75	3.55
Welcome Bay	CR059778	14.51	29.01	4.36	8.56	5.44	10.88	6.82	13.63	3.92	7.86
Kauri Point	DP547739	5.82	11.60	1.64	3.40	1.51	3.01	1.59	3.19	1.85	3.75
Tanners Point	DP912601	8.13	16.25	2.49	5.04	4.10	8.20	3.36	6.73	1.68	3.44
Waikareao	CR301357	13.13	26.25	10.59	21.19	6.34	12.68	8.02	16.04	2.11	4.39
Toll Bridge	DP952985	9.24	18.46	2.40	4.89	2.73	5.46	3.51	7.01	2.00	4.04
Tilby Point	EP118190	15.36	30.72	8.56	16.94	10.00	19.99	10.31	20.61	2.18	4.59

Table 17: *Effect of changes to river loading on water quality at monitoring sites (data shown in Figures 18 and 19) for summer scenarios. Colour indicates magnitude of change.*

Monitoring Site	Site ID	NO_3 (%)		NH_4 (%)		PO_4 (%)		TN (%)		ALGAE (%)	
		-20%	-40%	-20%	-40%	-20%	-40%	-20%	-40%	-20%	-40%
Entrance	CQ947053	2.78	5.55	0.33	0.71	0.46	0.91	0.72	1.44	0.90	1.81
Omokoroa	EP020617	9.33	18.52	2.63	5.41	1.90	3.80	2.70	5.40	3.58	7.24
Welcome Bay	CR059778	12.49	24.45	3.51	7.53	2.85	5.70	4.30	8.63	6.31	12.81
Kauri Point	DP547739	2.05	4.04	0.75	1.46	0.65	1.31	0.91	1.82	1.81	3.68
Tanners Point	DP912601	3.15	6.29	1.03	2.05	1.26	2.52	1.47	2.94	1.47	2.98
Waikareao	CR301357	13.18	26.36	3.89	7.42	3.05	6.10	6.04	12.08	4.58	9.21
Toll Bridge	DP952985	7.38	14.64	1.46	3.19	1.45	2.91	2.32	4.64	3.56	7.16
Tilby Point	EP118190	15.13	30.21	5.45	11.18	7.27	14.55	9.00	18.00	4.30	8.75

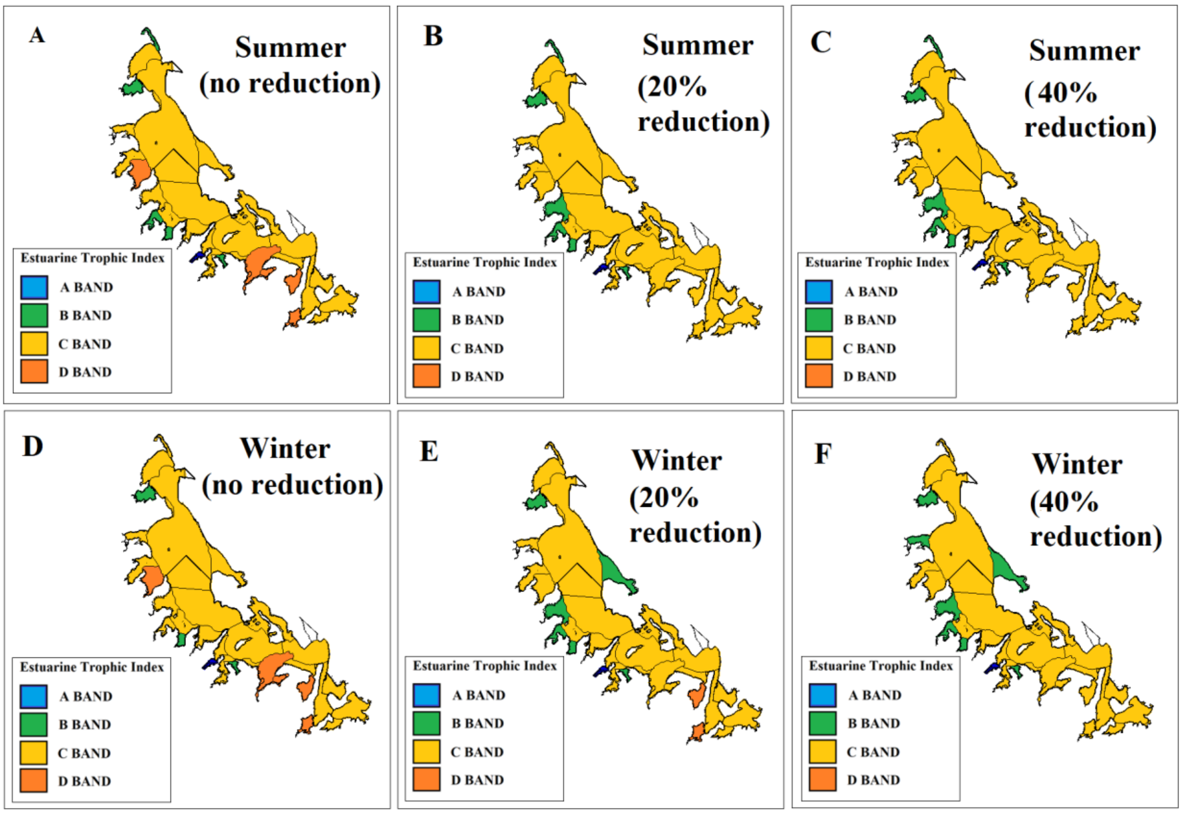

Figure 21: *Changes to ETI scores with winter and summer loading reduction scenarios.*

5. Summary and Outlook

A water quality study was undertaken to understand how nitrate, ammonium and phosphate might be distributed around Tauranga Harbour, and how the levels of these constituents might change with reductions in freshwater loading.

Areas that were in the immediate vicinity of large freshwater discharges, were strongly affected by the nature of that discharge (and responded well to loading reductions). However, the many shallow sub-estuaries with little freshwater input were not responsive enough to loading reductions to result in a change of classification in their susceptibility to enrichment such as macro-algal blooms. Processes in these areas are dominated by denitrification, and so remediation should focus on improving the condition of estuarine sediments. Managing and restoring habitats and key species that support effective sediment nitrogen cycling will be of paramount importance.

The modelling is heavily simplified, and nutrient loading only occurs from surface freshwater body sources, neglecting any input from groundwater or localised runoff (from leaky septic tanks and direct runoff from farming). We have some recent studies where we have attempted to measure groundwater nutrient contributions (Santos et al., 2014 and Stewart et al., 2018) and the contribution of shallow sub-estuaries to nutrient loading (Tay et al., 2011) mostly focused on the Waikareao and the Te Puna sub-estuaries. The Tay et al. (2011) study showed that there is a net flux of ammonium and nitrate out of these estuaries which does not come from the freshwater discharges, and which is highly seasonally variable, but is on the order of 50 kg/tidal cycle (which is ~1 g/s, similar to the loading from, for example the Aongatete, Tables 11 and 12). The source of this loading could be groundwater, direct run-off or breakdown of organic matter within the estuary. Santos et al. (2014) and Stewart et al., (2018) used radium and radon tracer techniques to show that the nutrients probably came from within the sediments (the ‘subterranean estuary’), and the contribution could be on the order of half the supply to the estuary. However, their technique cannot differentiate between nutrients sourced from groundwater, and those sourced deep within the sediments. One would expect a missing groundwater source in the model to be associated with modelled salinities being much too high, but Stewart (2021) showed that if anything, they were too low. Therefore, it was his conclusion that the groundwater source of nutrients in these small sub-estuaries was salty, and so likely related to decomposition and re-circulation of organic matter within the sediments. Perhaps the organic matter has accumulated over the last few decades, and is temporarily stored in the fine sediments of the upper harbour estuaries as a legacy of past catchment uses, to be gradually released into the main harbour over a longer timescale than the water column processes modelled here.

The water quality modules rely on many constants that are parameterised from literature values and some local studies in the Harbour such as the University of Waikato PhD thesis of Georgina Flowers on denitrification rates. These constants govern, for example, the transformation rate of different species of nitrogen (for example ammonium to nitrate), the uptake of light and nutrients by phytoplankton. Although we have had input over the years from Conrad Pilditch (on estuarine benthic functioning) and David Hamilton (water quality modelling) on what the most appropriate values for these settings are, ideally, they would be informed by local measurements on local species. The properties of these rates can also be set to time-dependant on physical processes in the DELWAQ water quality model. In our case, parameters like suspended sediment concentration and temperature were set constant for summer and winter conditions (listed in Tables 6 and 7). Although, this is an inherent limitation of water quality modelling in an estuary as large and complex as Tauranga Harbour, where there can be relatively long timescales and distances between the point where the loading occurs and the ultimate sink in the ocean, it still provides robust and useful information for planning. As long as we focus on general seasonal patterns that have multiple lines of evidence confirming them (such as the residence time, the source-sink analysis and the comparison to observation points).

6. Acknowledgements

This research was funded by Bay of Plenty Regional Council. We thank Josie Crawshaw, Nicola Green, Stephen Park and Rochelle Carter of Bay of Plenty Regional Council for their reviews. Peter de Ruiter provided model grid and bathymetry files for hydrodynamic runs. Conrad Pilditch and Georgina Flowers provided input on denitrification rates.

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APPENDIX 1: Maps of Observations Areas

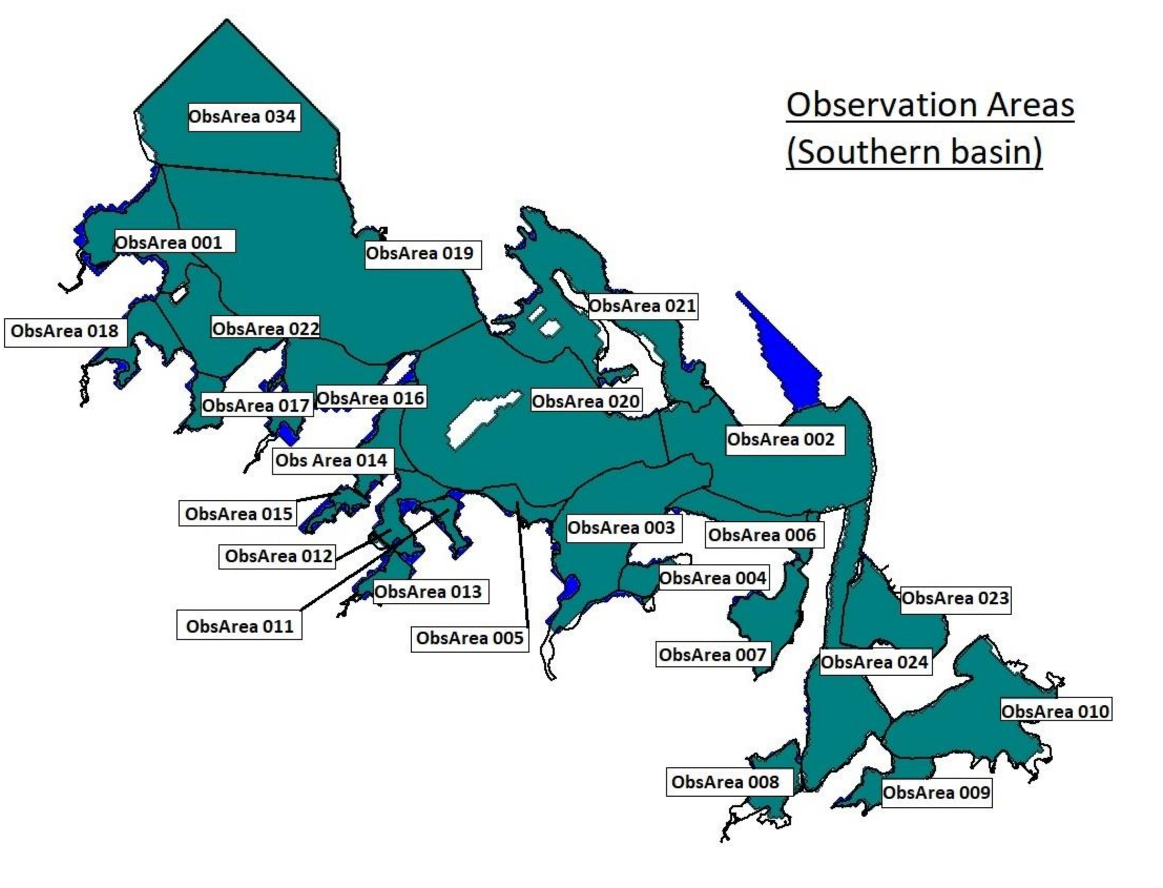


Figure A1: *Map of observations points used in the source-sink analysis (Southern Harbour).*

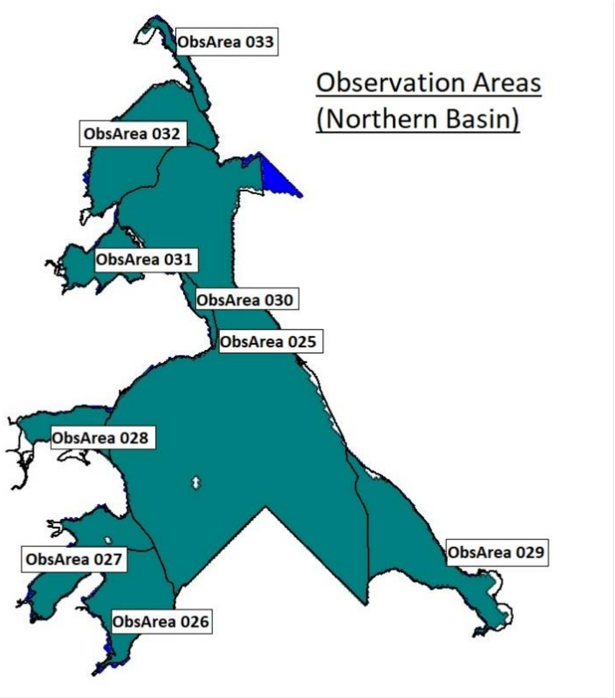


Figure A2: *Map of the observations points used in the source-sink analysis (Northern Harbour).*

APPENDIX 2: River discharge predictions

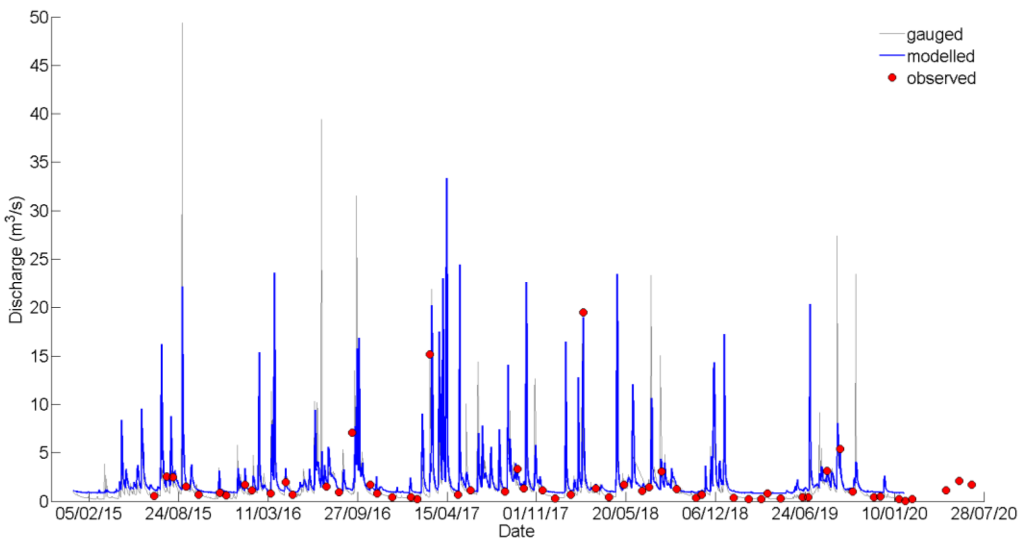


Figure A3*: Reconstructed river discharge of Aongatete River (blue) using Tuapiro discharge data (gauge) as a predictor.*

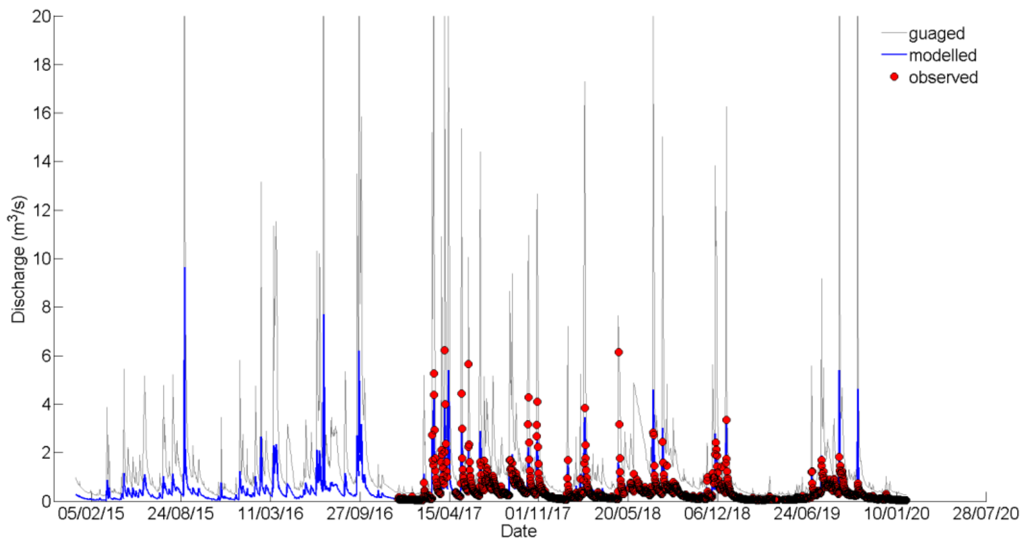


Figure A4*: Reconstructed river discharge of Te Mania (blue) stream using Tuapiro discharge data (grey) as a predictor.*

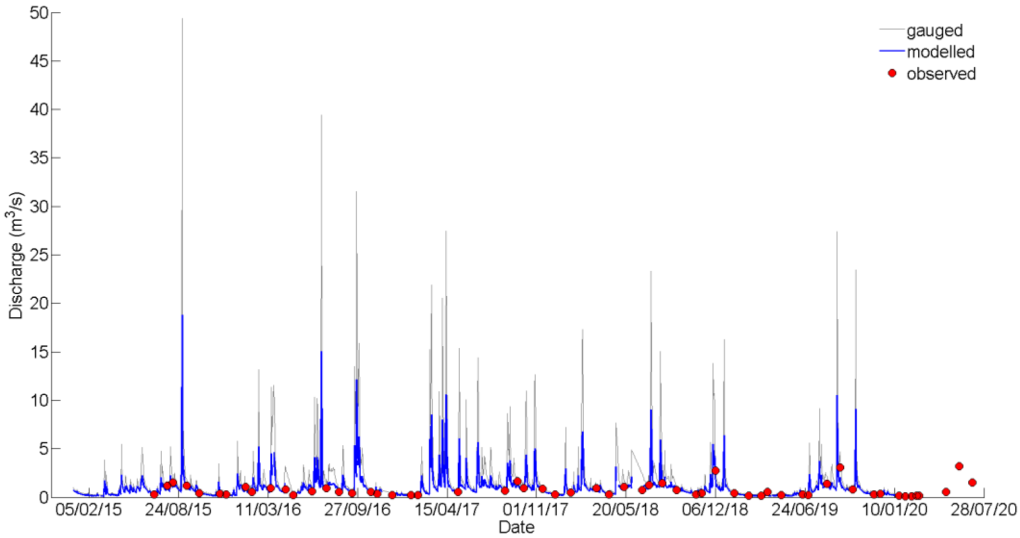


Figure A5*: Reconstructed river discharge of Uretara stream (blue) using Tuapiro discharge data (grey) as a predictor.*

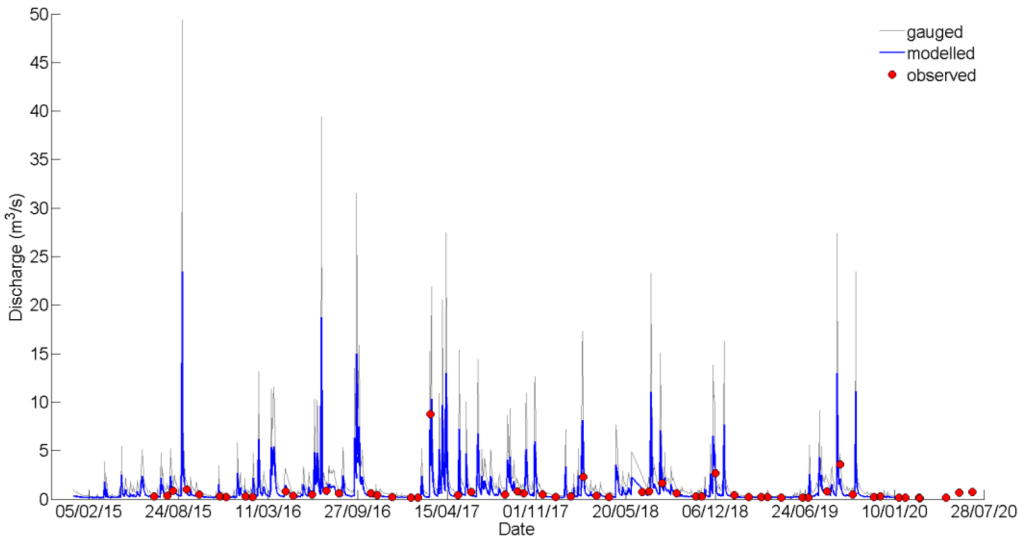


Figure A6*: Reconstructed river discharge of Waiau Stream (blue) using Tuapiro discharge data (grey) as a predictor.*

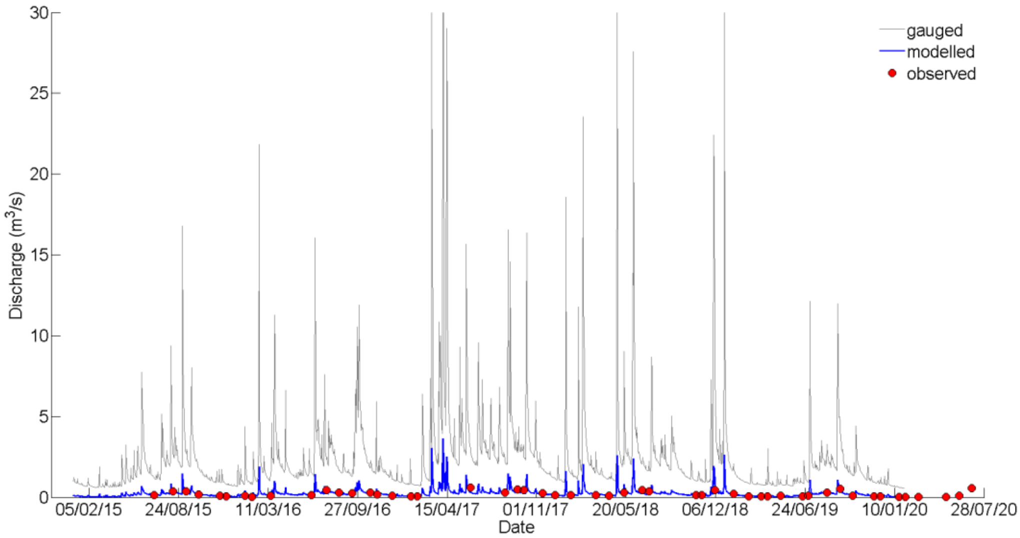


Figure A7: *Reconstructed river discharge of Rocky Stream (blue) using Waimapu discharge data (grey) as a predictor.*

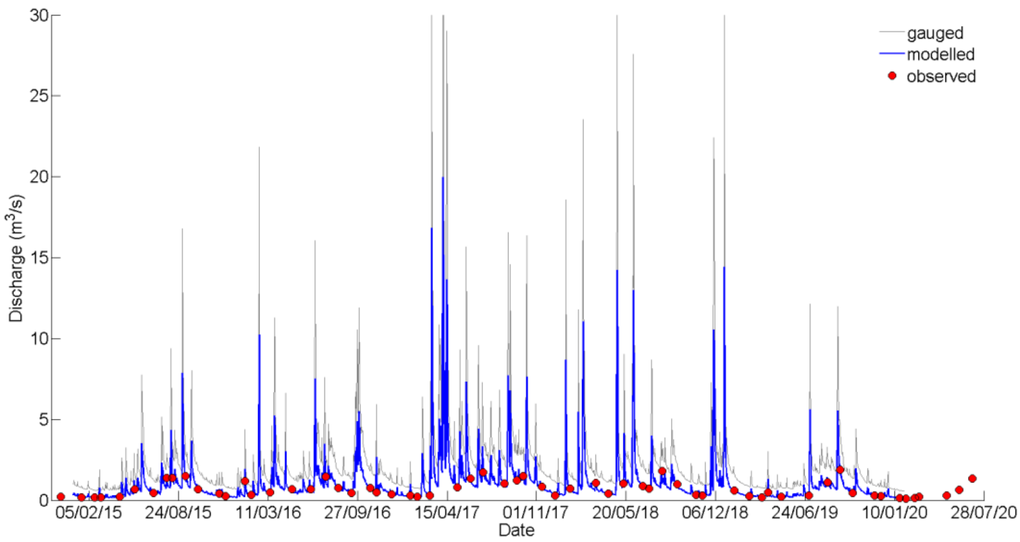


Figure A8: *Reconstructed river discharge of Waitao Stream (blue) using Waimapu discharge data (grey) as a predictor.*

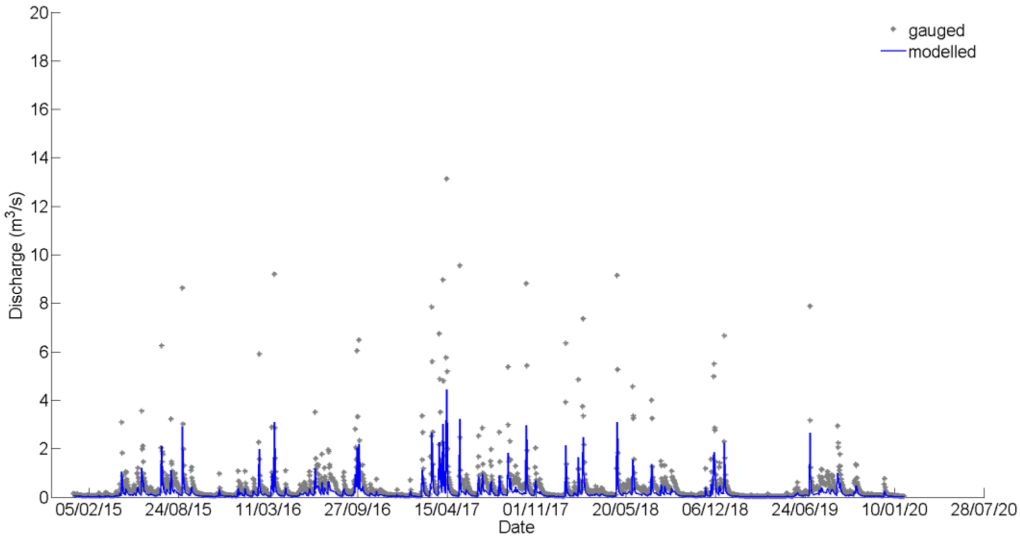


***Figure A9**: Reconstructed river discharge of Apata Stream (blue), calculated by scaling the Waipapa discharge prediction (grey) by the difference in catchment size.*

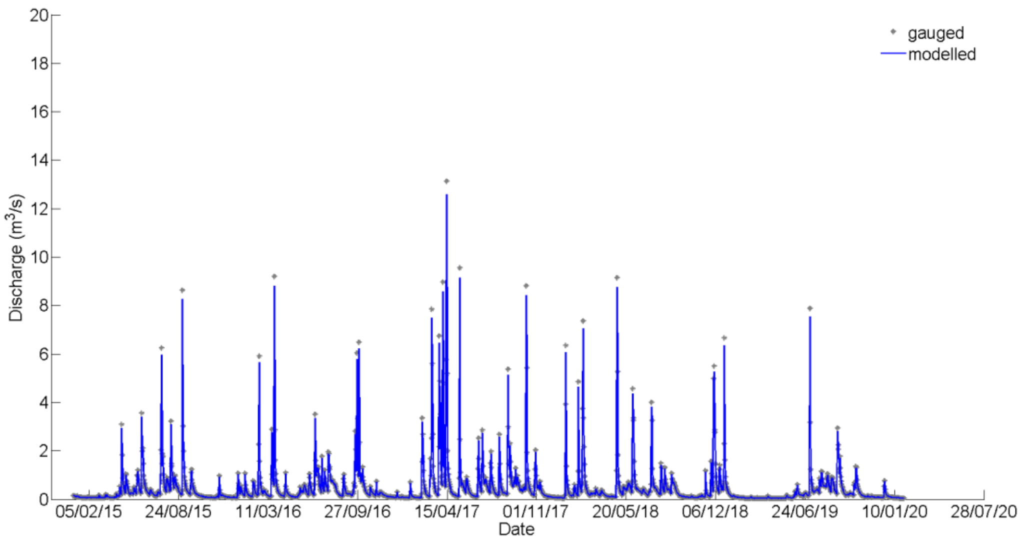


***Figure A10**: Reconstructed river discharge of Wainui Stream (blue), calculated by scaling the Waipapa discharge prediction (grey) by the difference in catchment size.*

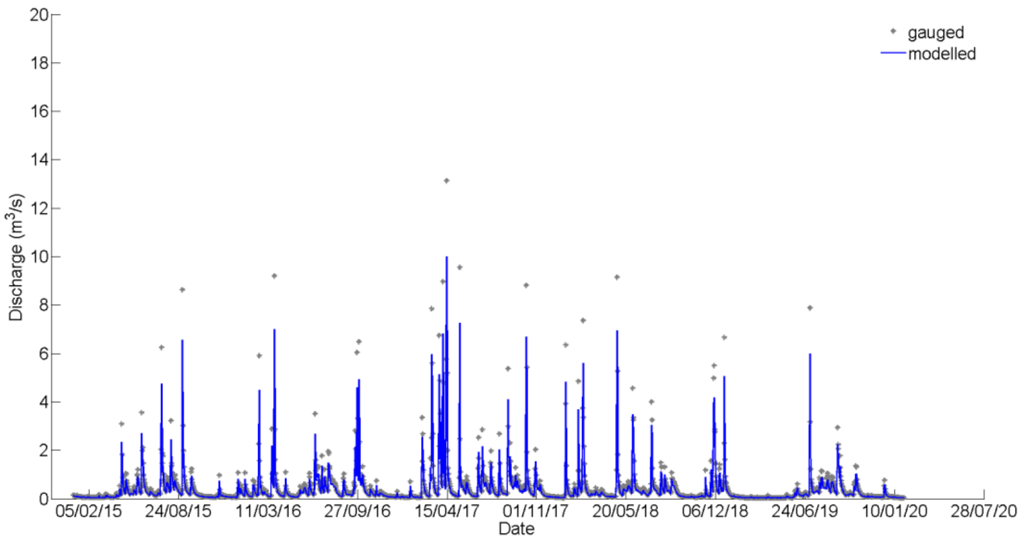


***Figure A11**: Reconstructed river discharge of Te Puna Stream (blue), calculated by scaling the Waipapa discharge prediction (grey) by the difference in catchment size.*

APPENDIX 3: Nutrient verification

Entrance

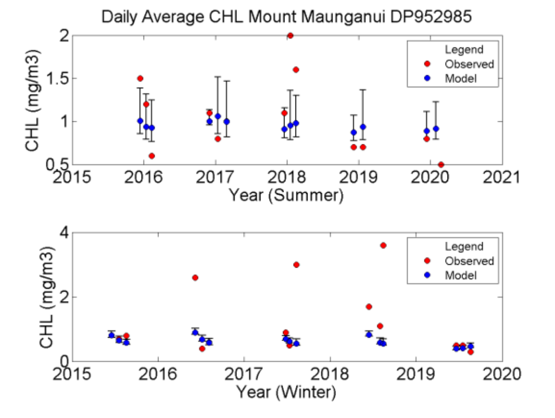


Figure A12*: Observed and modelled Chl-a concentration for the Entrance monitoring site. Error bars represent variability over a day.*

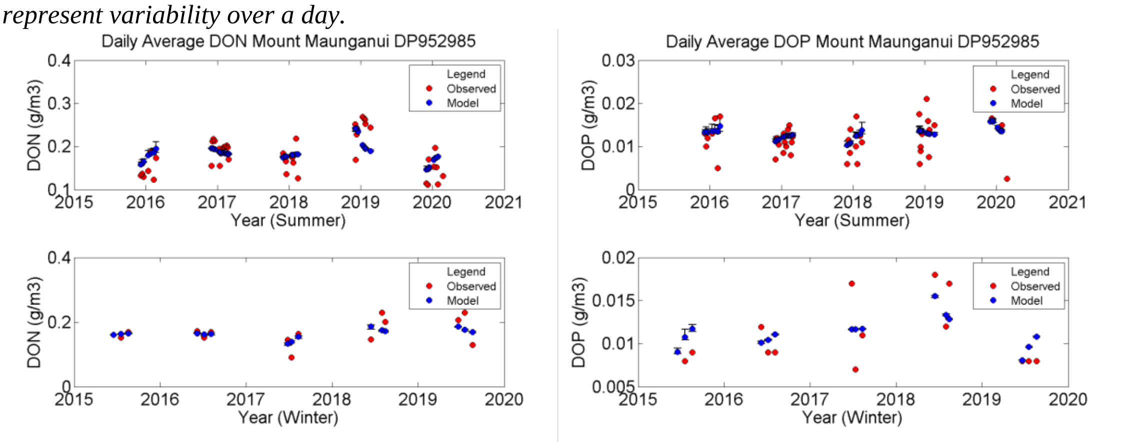
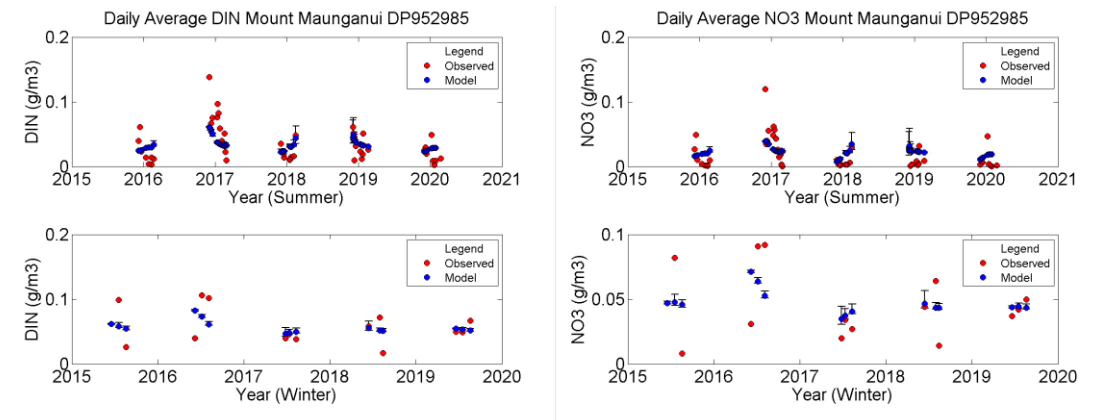


Figure A13*: Observed and modelled DON and DOP concentrations for Entrance monitoring site. Error bars represent variability over a day.*



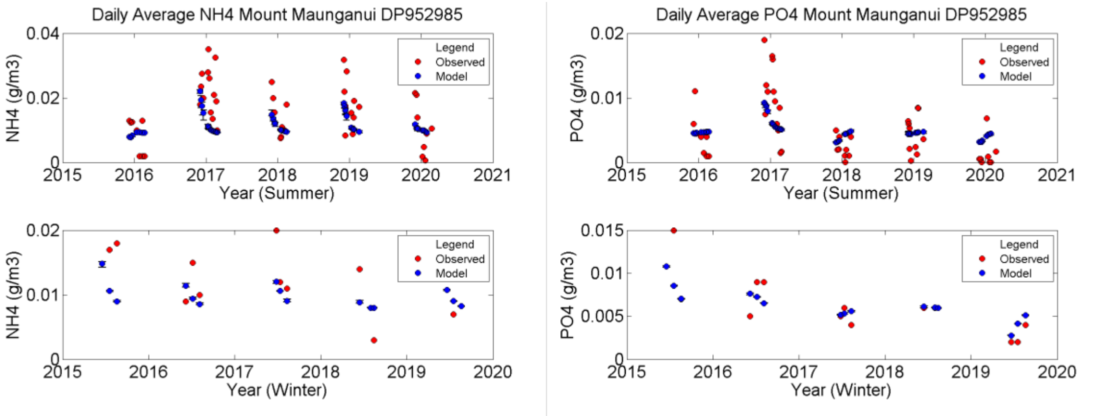


***Figure A14**: Observed and modelled DIN, NO_3^-, NH_4^+ and PO_4^{3-} concentrations for the Entrance monitoring site. Error bars represent variability over a day.*

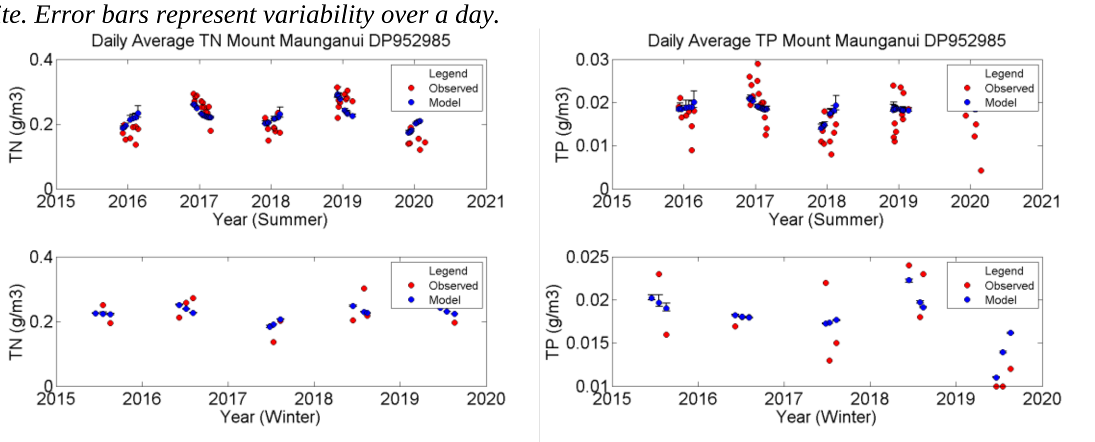


***Figure A15**: Observed and modelled TN and TP concentrations for the Entrance monitoring site. Error bars represent variability over a day.*

Kauri Point

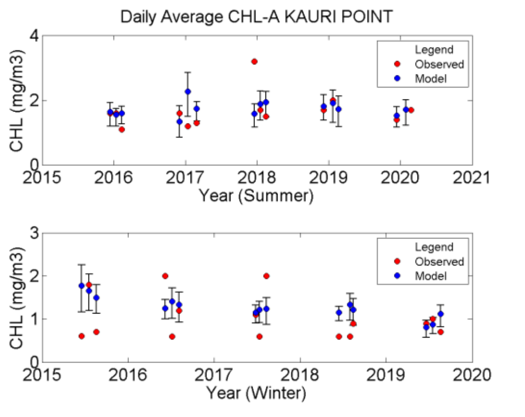


***Figure A16**: Observed and modelled Chl-a concentration for Kauri Point monitoring site. Error bars represent variability over a day.*

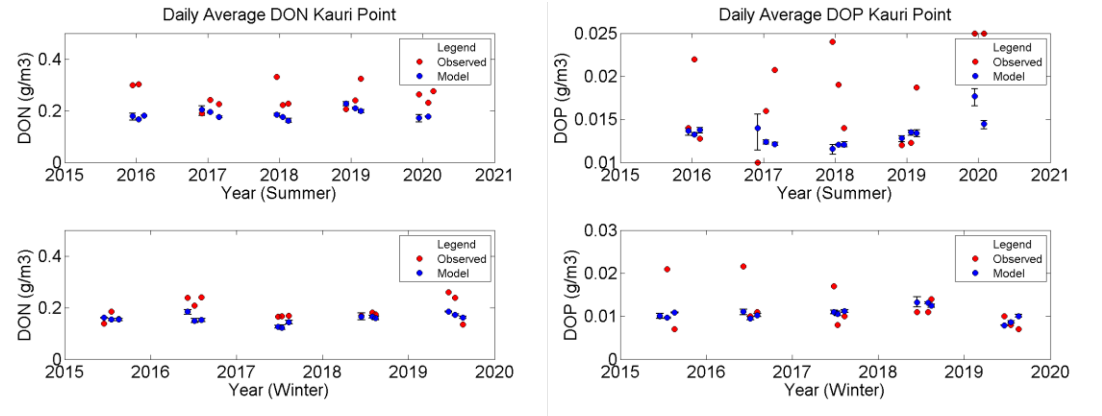


Figure A17: *Observed and modelled DON and DOP concentrations for Kauri Point monitoring site. Error bars represent variability over a day.*

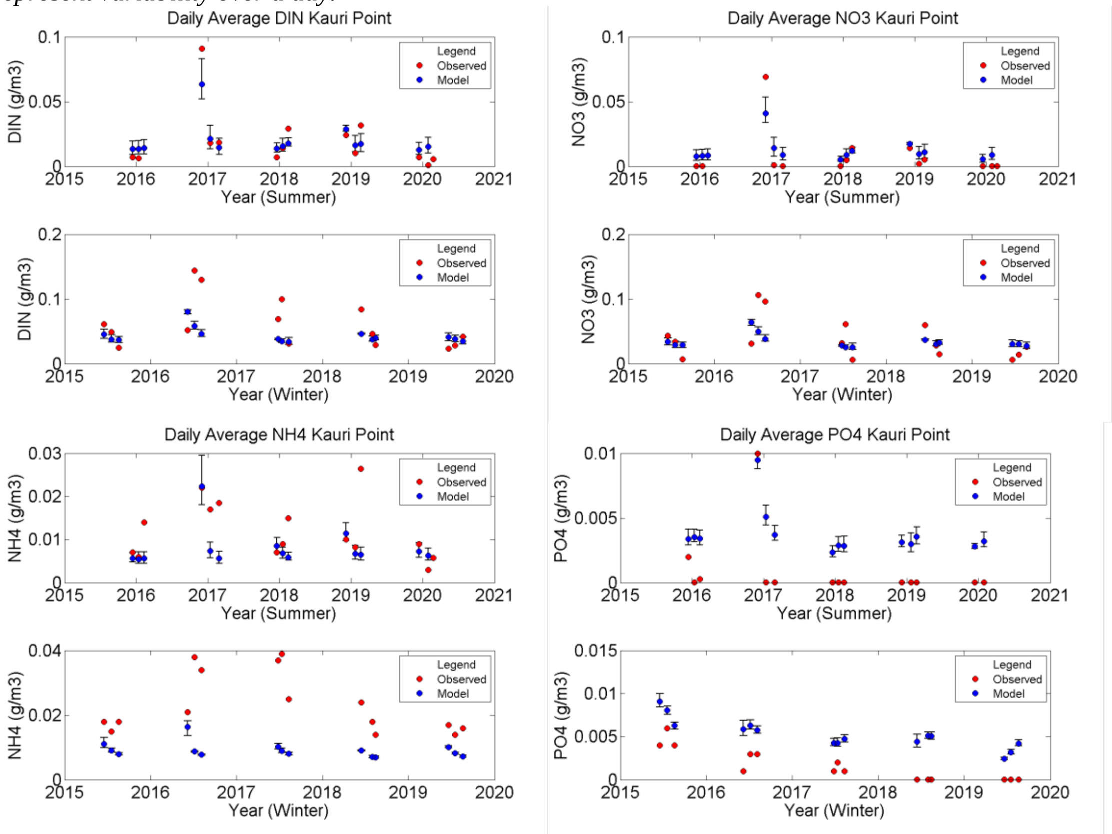


Figure A18: *Observed and modelled DIN, NO_3^-, NH_4^+ and PO_4^{3-} concentrations for Kauri Point monitoring site. Error bars represent variability over a day.*

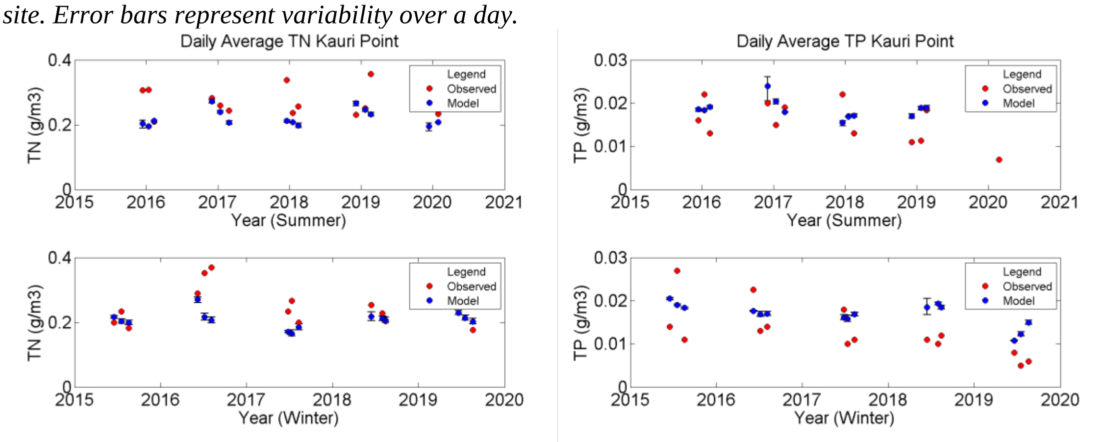


Figure A19: *Observed and modelled TN and TP concentrations for Kauri Point monitoring site. Error bars represent variability over a day.*

Omokoroa

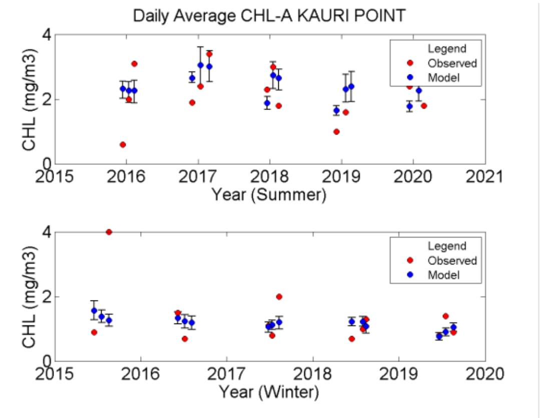


Figure A20*: Observed and modelled Chl-a concentration for Ōmokoroa monitoring site. Error bars represent variability over a day.*

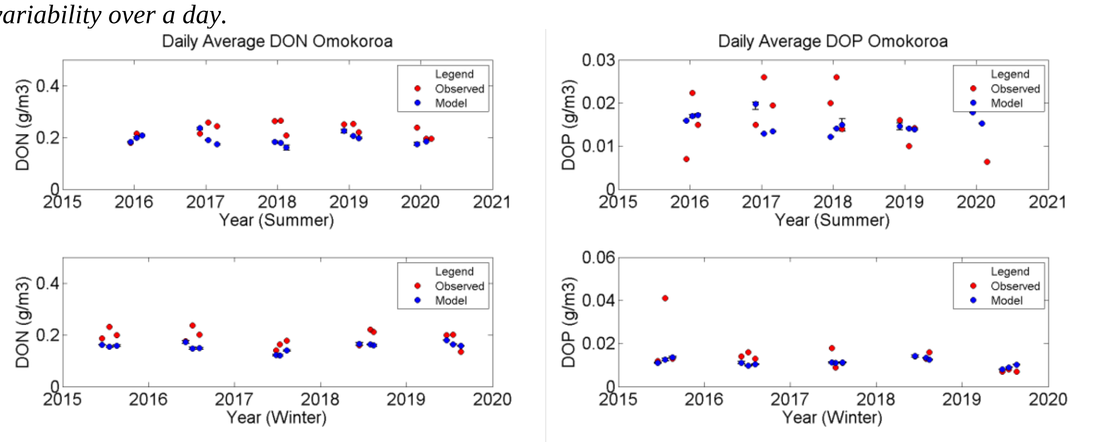


Figure A21*: Observed and modelled DON and DOP concentrations for Ōmokoroa monitoring site. Error bars represent variability over a day.*

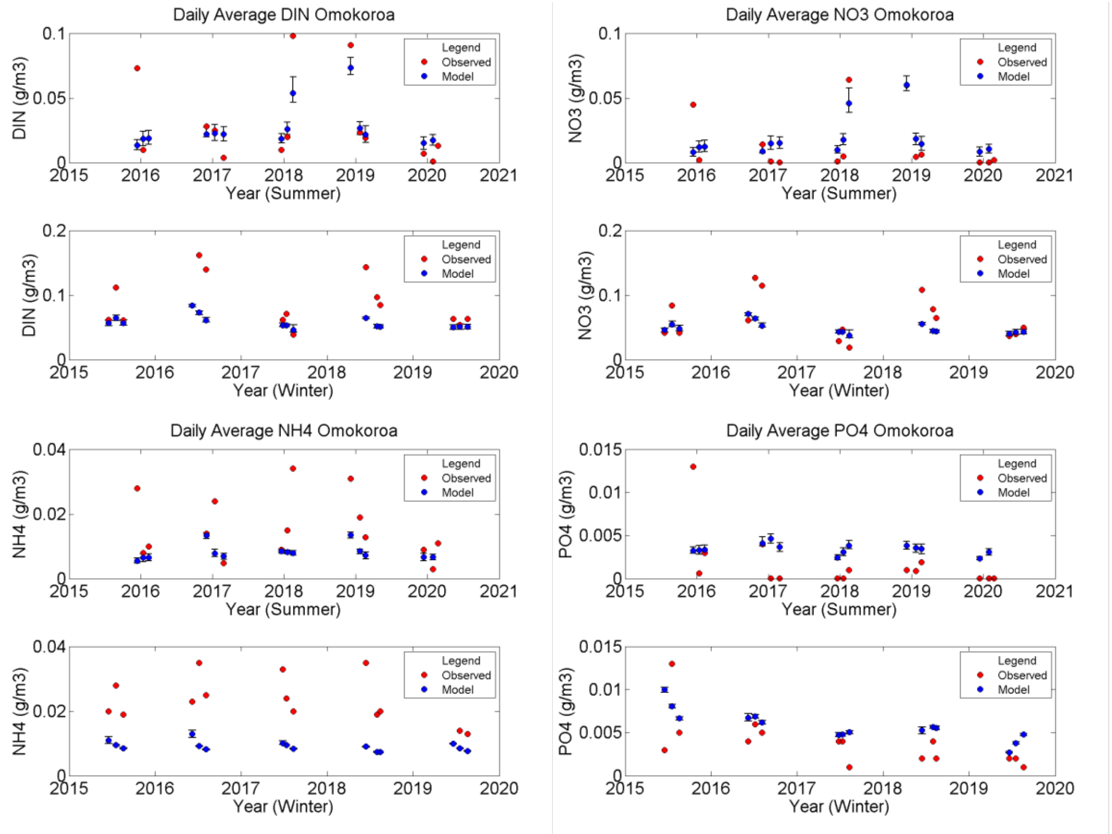


***Figure A22**: Observed and modelled DIN, NO_3^-, NH_4^+ and PO_4^{3-} concentrations for Ōmokoroa monitoring site. Error bars represent variability over a day.*

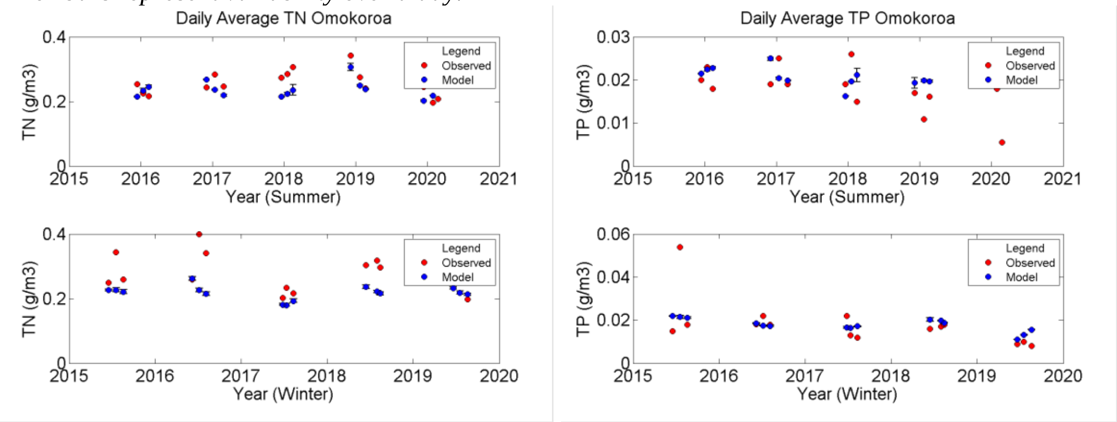


***Figure A23**: Observed and modelled TN and TP concentrations for Ōmokoroa monitoring site. Error bars represent variability over a day.*

Tanners Point

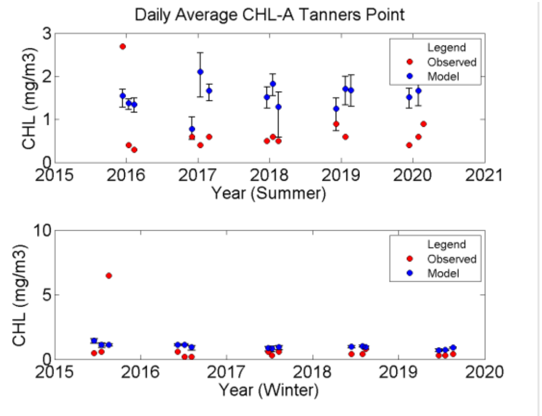


***Figure A24**: Observed and modelled Chl-a concentration for Tanners Point monitoring site. Error bars represent variability over a day.*

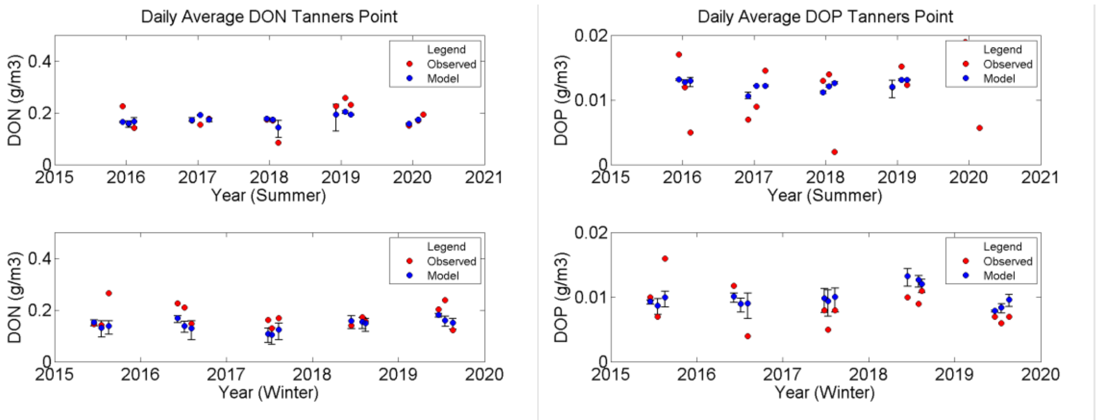


***Figure A25**: Observed and modelled DON and DOP concentrations for Tanners Point monitoring site. Error bars represent variability over a day.*

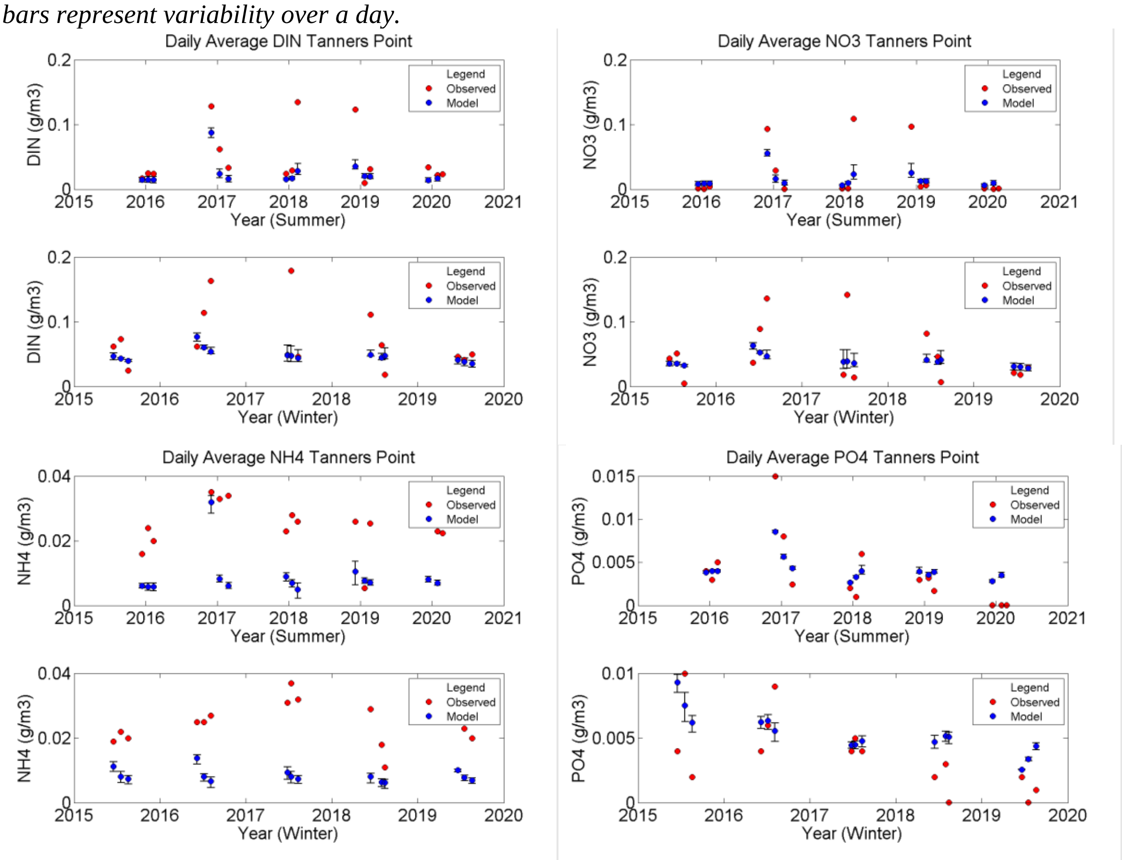


***Figure A26**: Observed and modelled DIN, NO_3^-, NH_4^+ and PO_4^{3-} concentrations for Tanners Point monitoring site. Error bars represent variability over a day.*

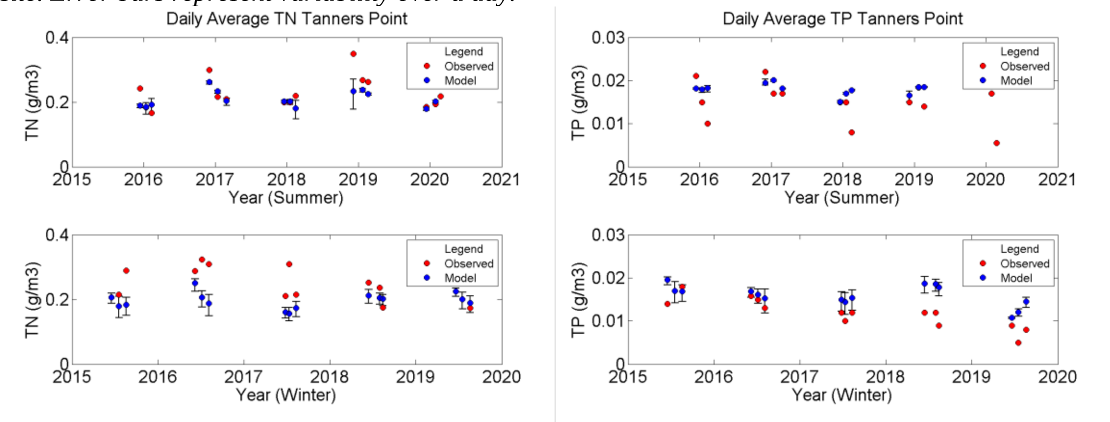


***Figure A27**: Observed and modelled TN and TP concentrations for Tanners Point monitoring site. Error bars represent variability over a day.*

Tilby Point

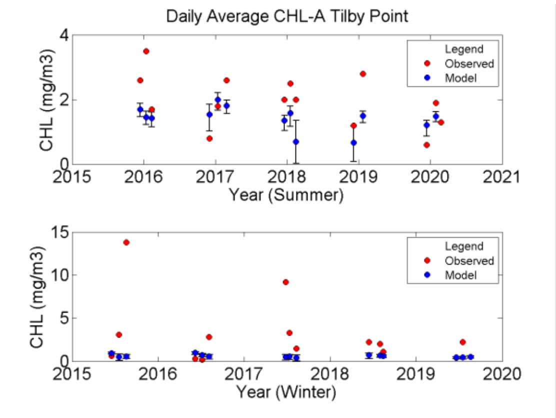


***Figure A28**: Observed and modelled Chl-a concentration for Tilby Point monitoring site. Error bars represent variability over a day.*

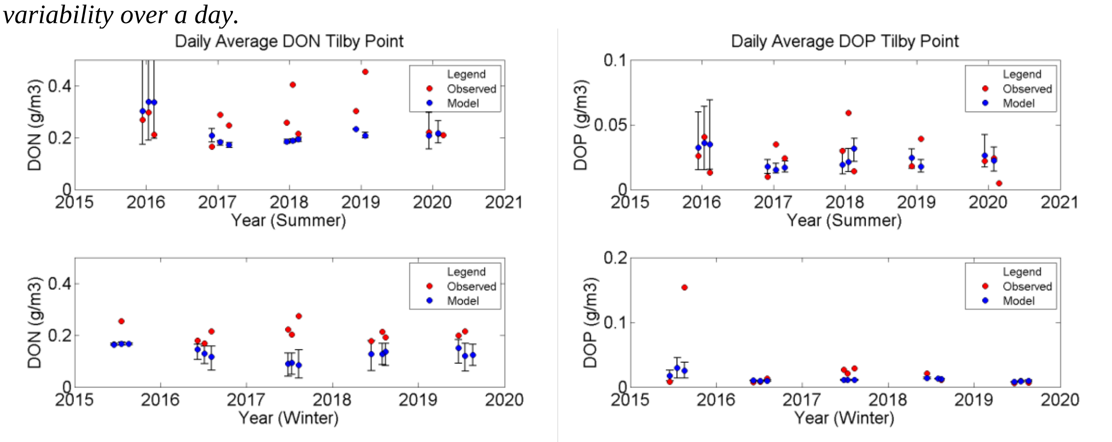


***Figure A29**: Observed and modelled DON and DOP concentrations for Tilby Point monitoring site. Error bars represent variability over a day.*

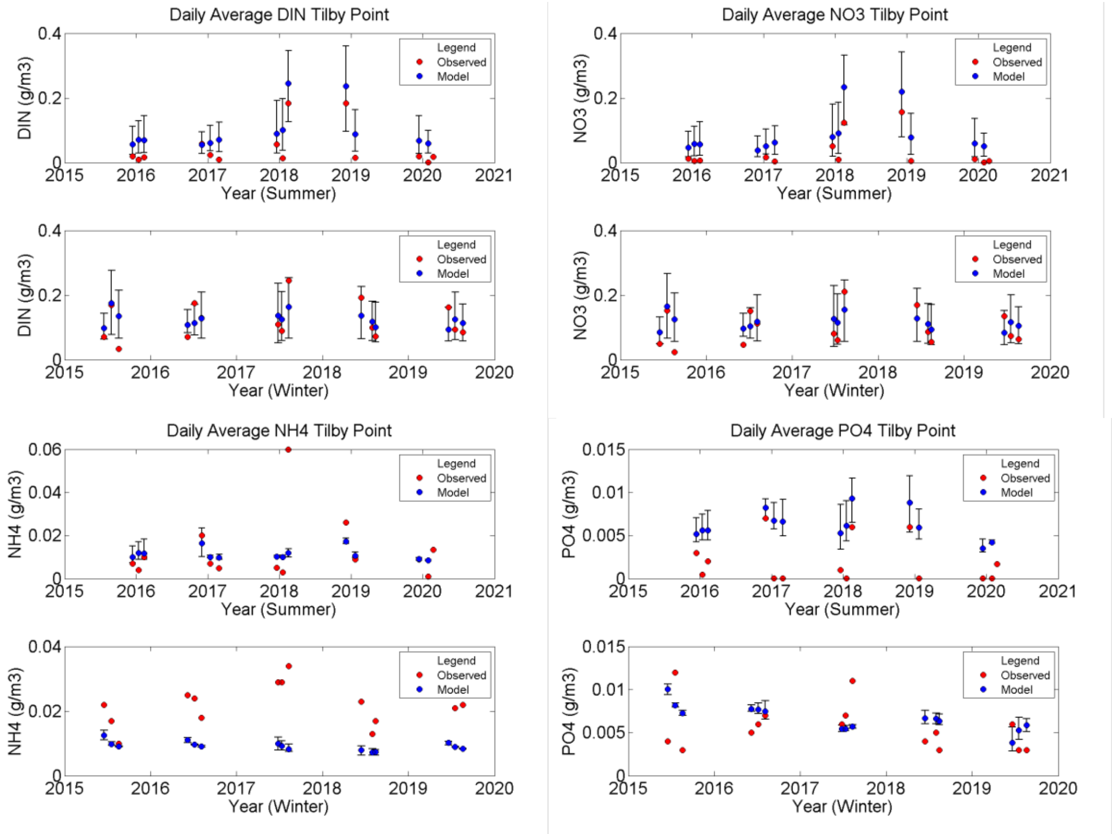


Figure A30*: Observed and modelled DIN, NO_3^-, NH_4^+ and PO_4^{3-} concentrations for Tilby Point monitoring site. Error bars represent variability over a day.*

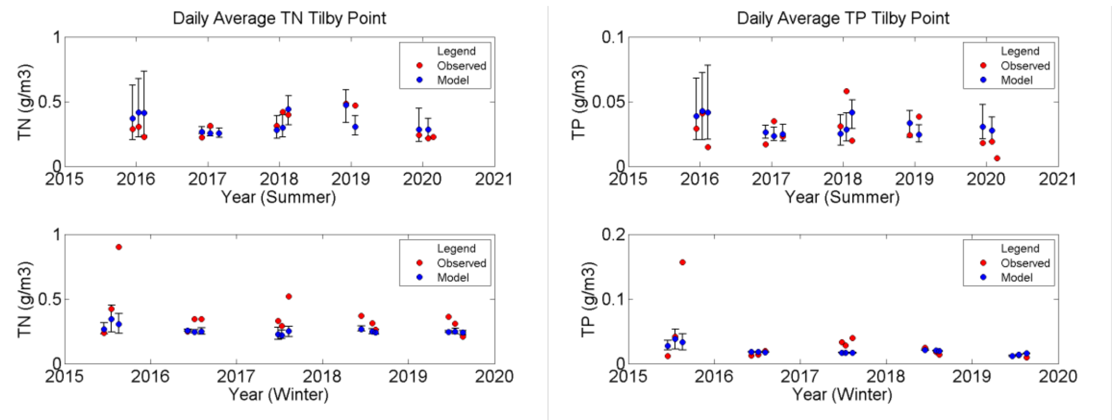


Figure A31*: Observed and modelled TN and TP concentrations for Tilby Point monitoring site. Error bars represent variability over a day.*

Toll Bridge

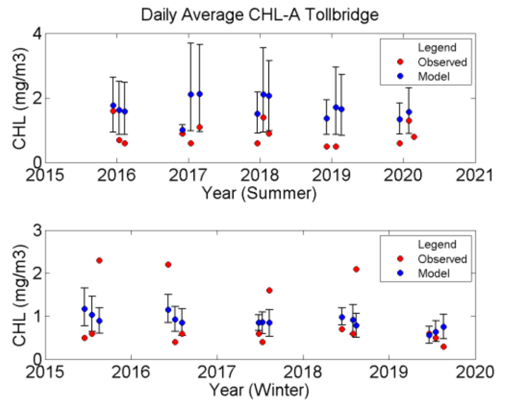


***Figure A32**: Observed and modelled Chl-a concentration for Toll Bridge monitoring site. Error bars represent variability over a day.*

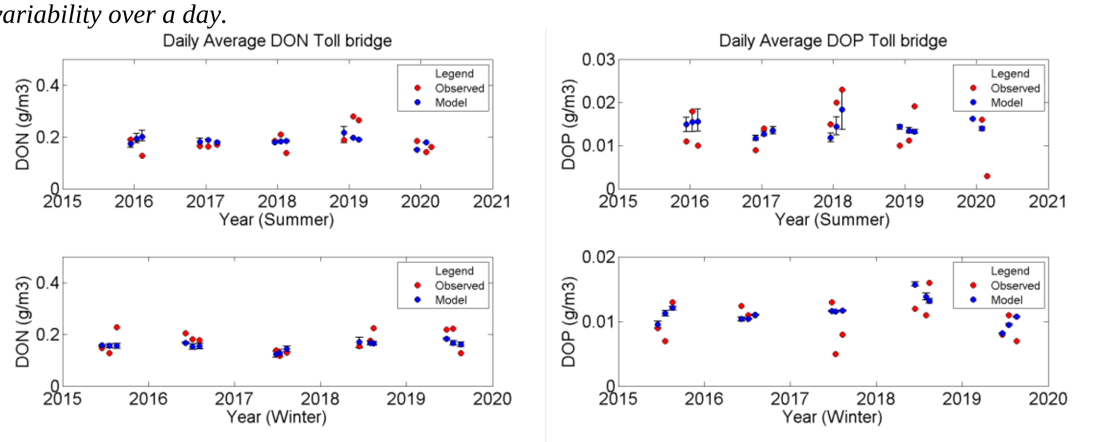


***Figure A33**: Observed and modelled DON and DOP concentrations for Toll Bridge monitoring site. Error bars represent variability over a day.*

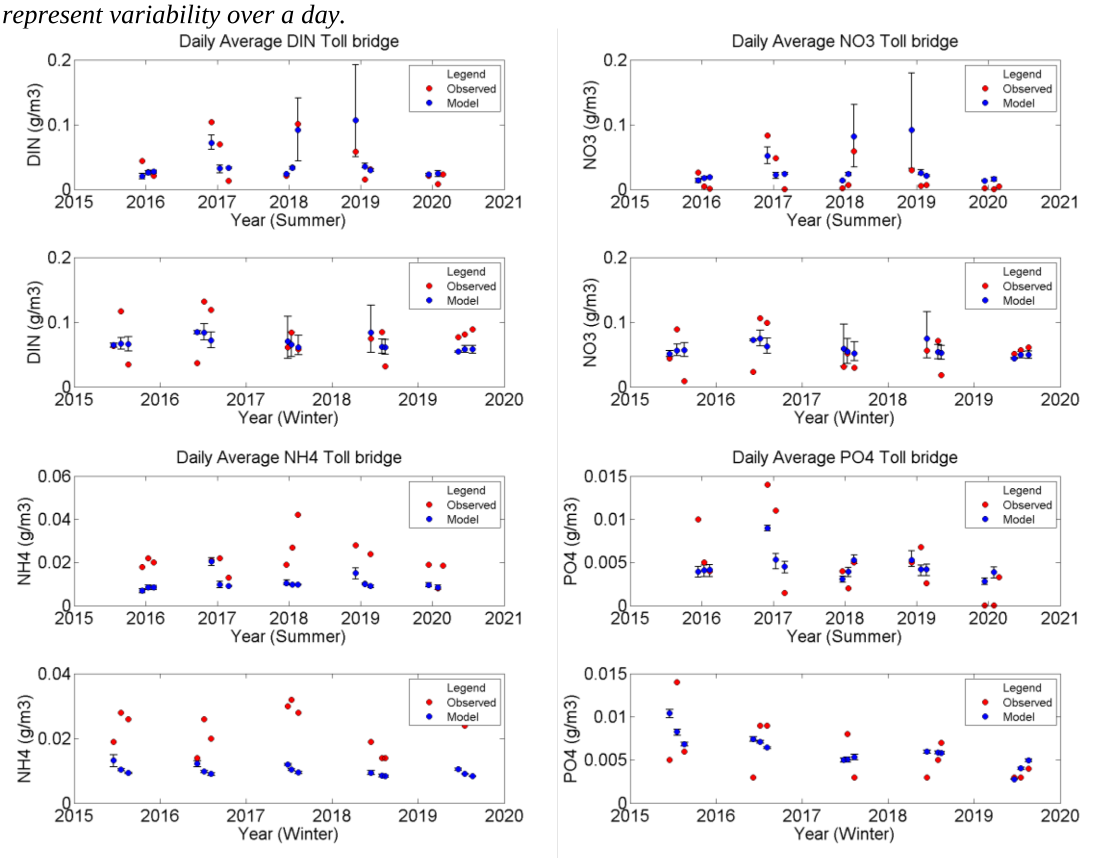


***Figure A34**: Observed and modelled DIN, NO_3^-, NH_4^+ and PO_4^{3-} concentrations for Toll Bridge monitoring site. Error bars represent variability over a day.*

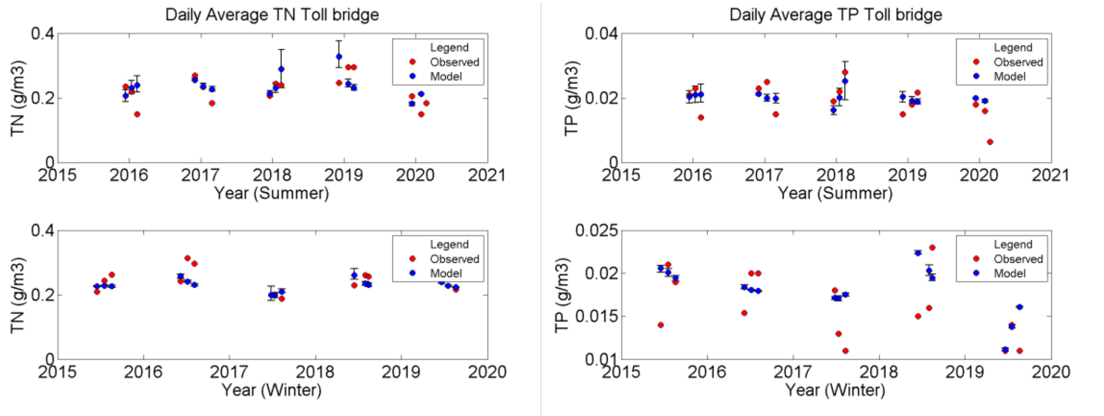


Figure A35*: Observed and modelled TN and TP concentrations for Toll Bridge monitoring site. Error bars represent variability over a day.*

Waikaraeo

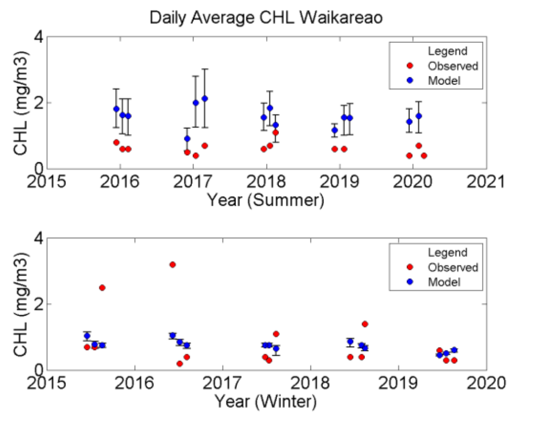


Figure A36*: Observed and modelled Chl-a concentration for Waikaraeo monitoring site. Error bars represent variability over a day.*

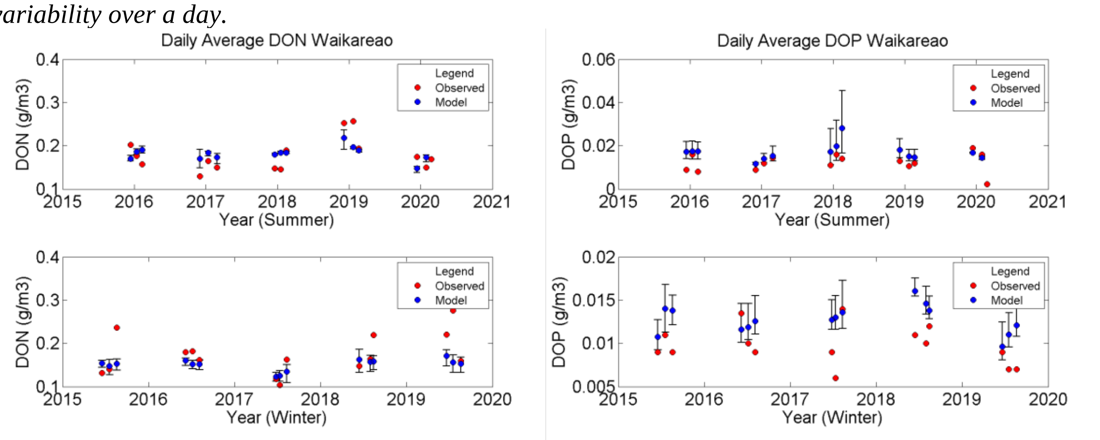


Figure A37*: Observed and modelled DON and DOP concentrations for Waikaraeo monitoring site. Error bars represent variability over a day.*

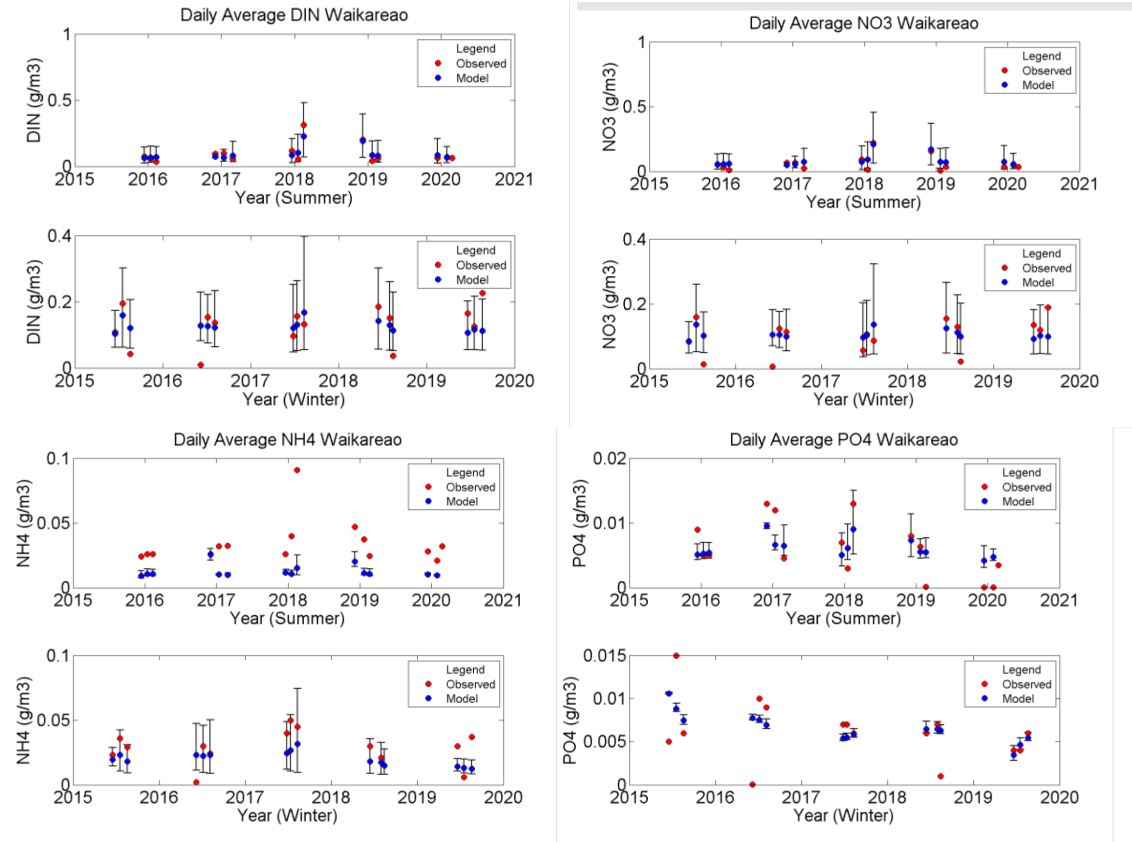


***Figure A38**: Observed and modelled DIN, NO_3^-, NH_4^+ and PO_4^{3-} concentrations for Waikaraeo monitoring site. Error bars represent variability over a day.*

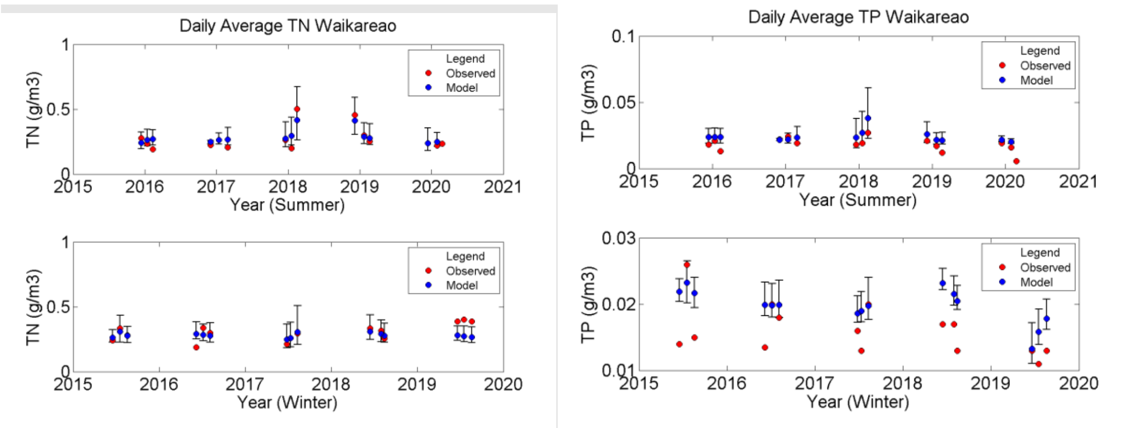


***Figure A39**: Observed and modelled TN and TP concentrations for Waikaraeo monitoring site. Error bars represent variability over a day.*

Welcome Bay

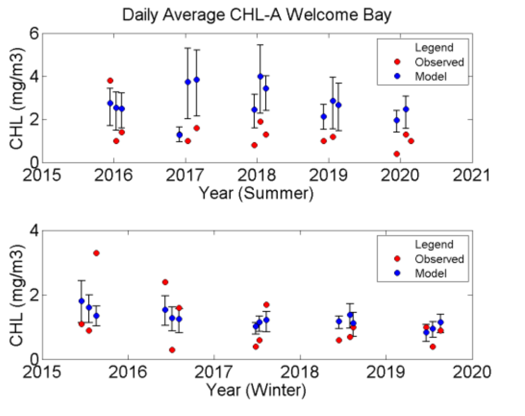


Figure A40: *Observed and modelled Chl-a concentration for Welcome Bay monitoring site. Error bars represent variability over a day.*

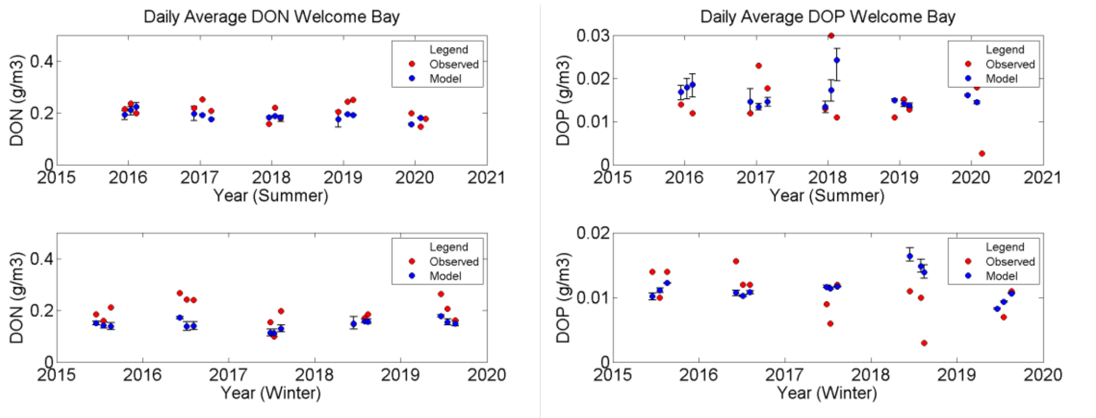


Figure A41: *Observed and modelled DON and DOP concentrations for Welcome Bay monitoring site. Error bars represent variability over a day.*

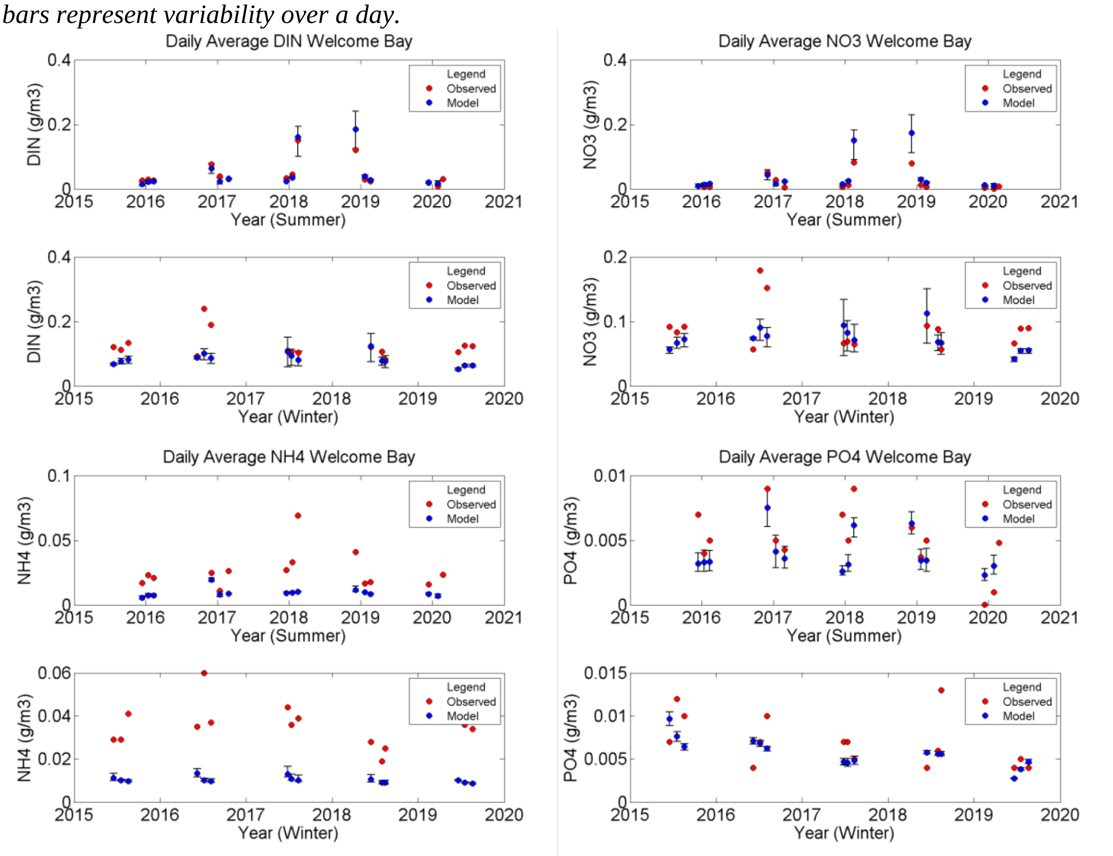


***Figure A42**: Observed and modelled DIN, NO_3^-, NH_4^+ and PO_4^{3-} concentrations for Welcome Bay monitoring site. Error bars represent variability over a day.*

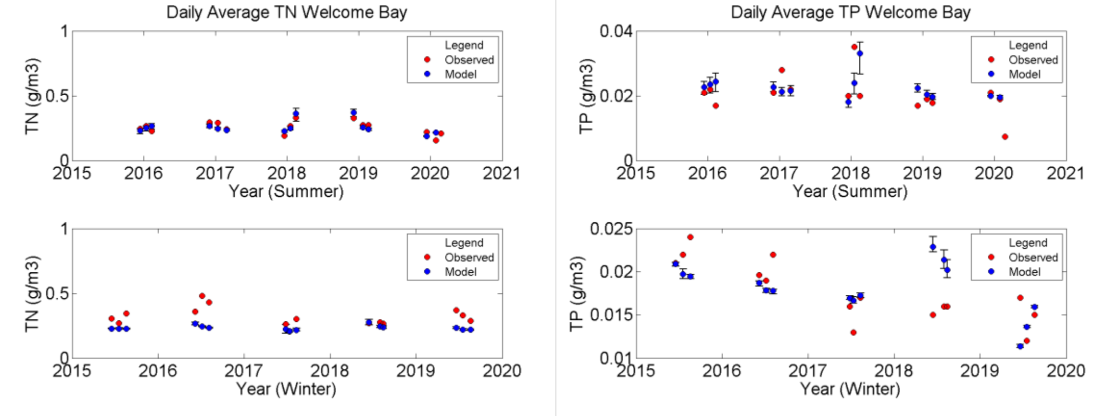


***Figure A43**: Observed and modelled TN and TP concentrations for Welcome Bay monitoring site. Error bars represent variability over a day.*

APPENDIX 4: Calibration Statistics

Statistical analyses (bias, accuracy, and skill) were based on Sutherland et al. (2004). Bias was determined following the equation:

$$Bias = \frac{1}{J}\sum_{j=1}^{J}(y_j - x_j) = \langle Y \rangle - \langle X \rangle$$

where Y is the model results, X is the measured data, J is the number of predictions and observations occurring at the same time and location. Angular brackets represent the mean.

Accuracy was determined by the Mean Absolute Error (MAE) and by the root mean square error (RMSE):

$$MAE = \frac{1}{J}\sum_{j=1}^{J}(y_j - x_j) = \langle |Y - X| \rangle$$

$$RMSE = \sqrt{\frac{1}{J}\sum_{j=1}^{J}(y_j - x_j)^2} = \sqrt{\langle (Y - X)^2 \rangle}$$

where straight brackets represent the absolute value of the errors.

Bias was calculated using the following equation:

$$BSS = 1 - \frac{MSE(Y,X)}{MSE(B,X)} = 1 - \frac{\langle (Y - X)^2 \rangle}{\langle (B - X)^2 \rangle}$$

where B is the average of measured data.

The classification based on BSS score ranges from bad to excellent according to Sutherland et al. (2004):

BSS score	Classification
BSS <0.0	bad
0.0> BSS <0.1	poor
0.1> BSS <0.2	reasonable/fair
0.2> BSS <0.5	good
0.5> BSS <1.0	excellent

APPENDIX 5: Salinity verification

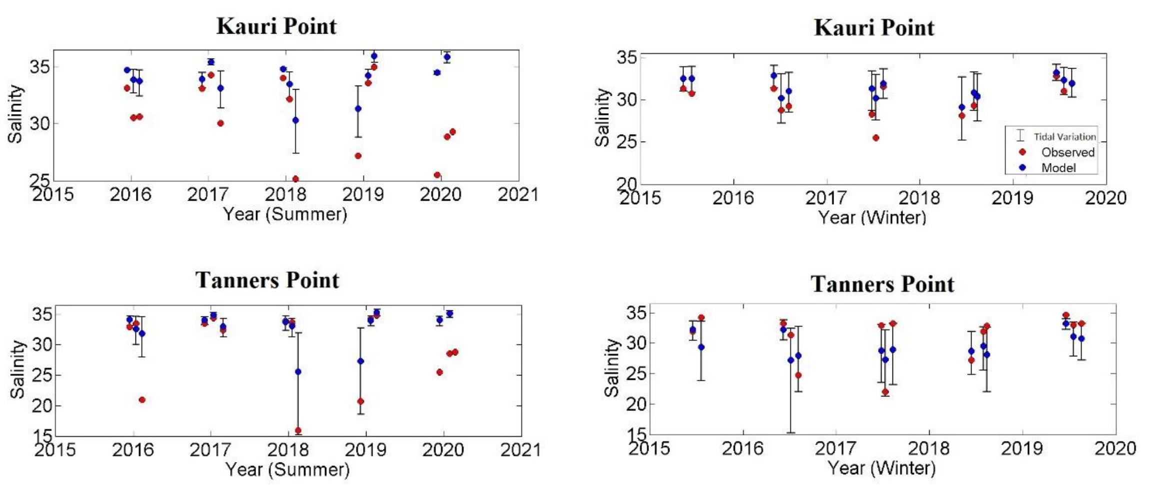


***Figure A44**: Observed and modelled salinity for northern harbour sampling sites. Error bars represent variability over a day.*

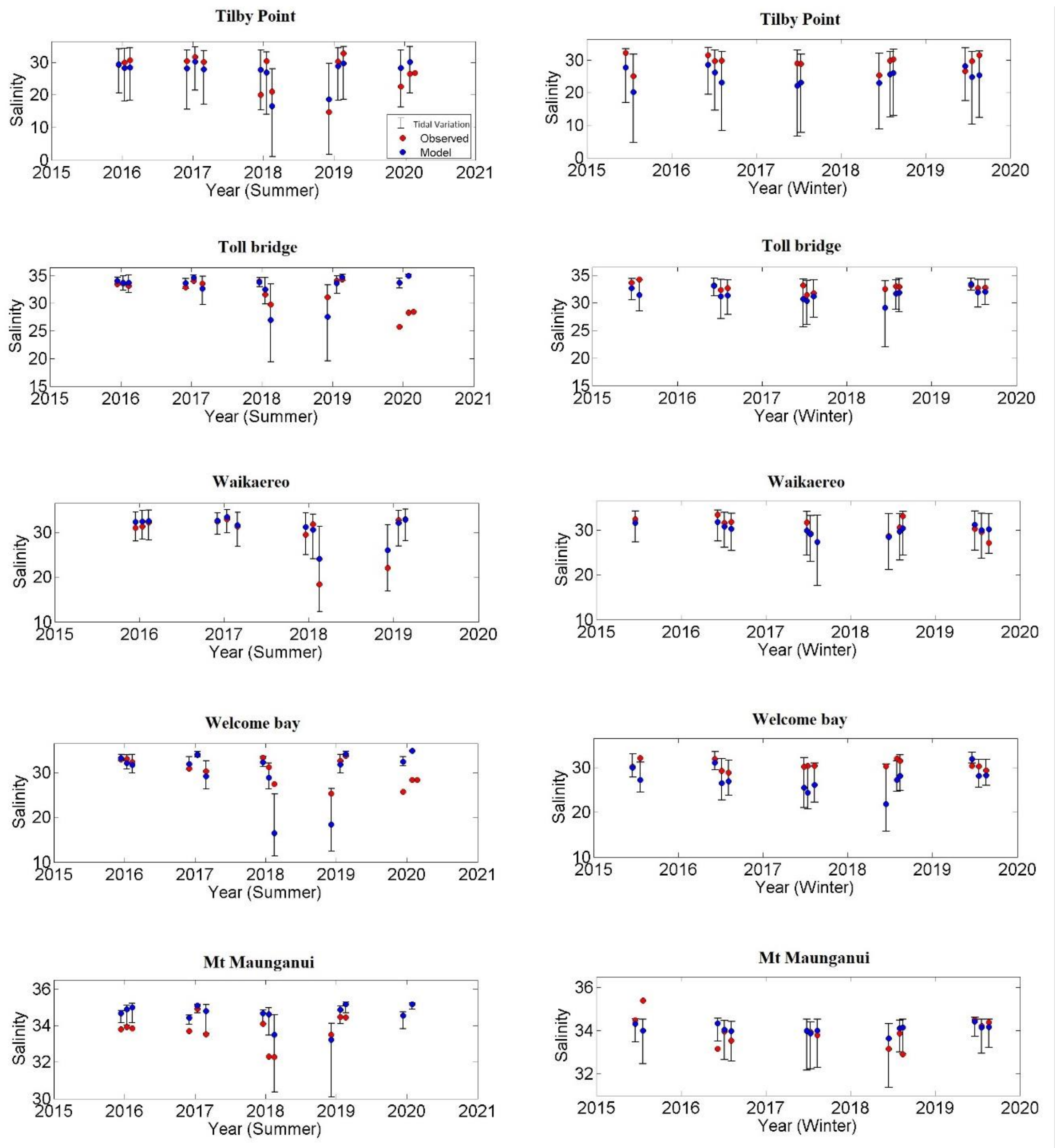


***Figure A45**: Observed and modelled salinity for southern harbour sampling sites. Error bars represent variability over a day.*

APPENDIX 6: Source Sink Analysis

This Appendix shows the net contribution of each region to each other region (a graphical representation of the material in Tables 14 and 15).

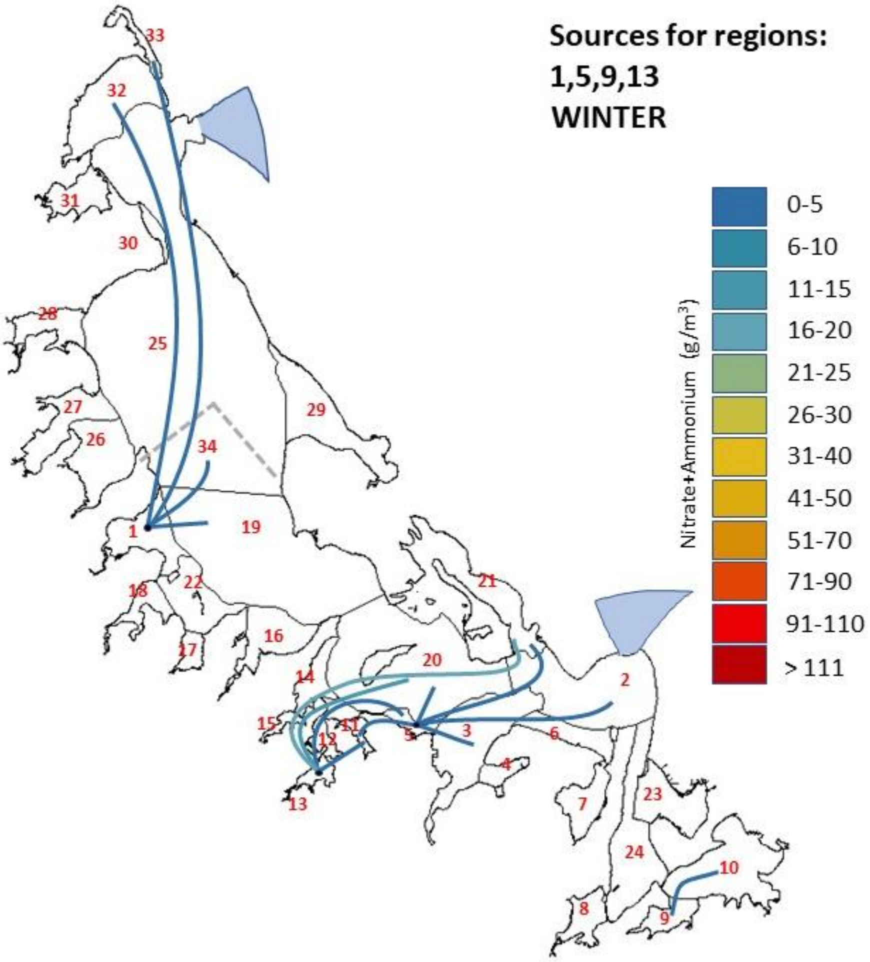


***Figure A46**: Net sources/sinks of nitrate and ammonium for regions 1,5,9,13 for winter. For example, region 1 is connected most to regions 33, 32 34 and 19. No lines are plotted where the sources and sinks exactly balance, or where there is no contribution. In order for nutrients to move from area 1 to area 32, they pass through area 25, but do not cause a significant net change to area 25.*

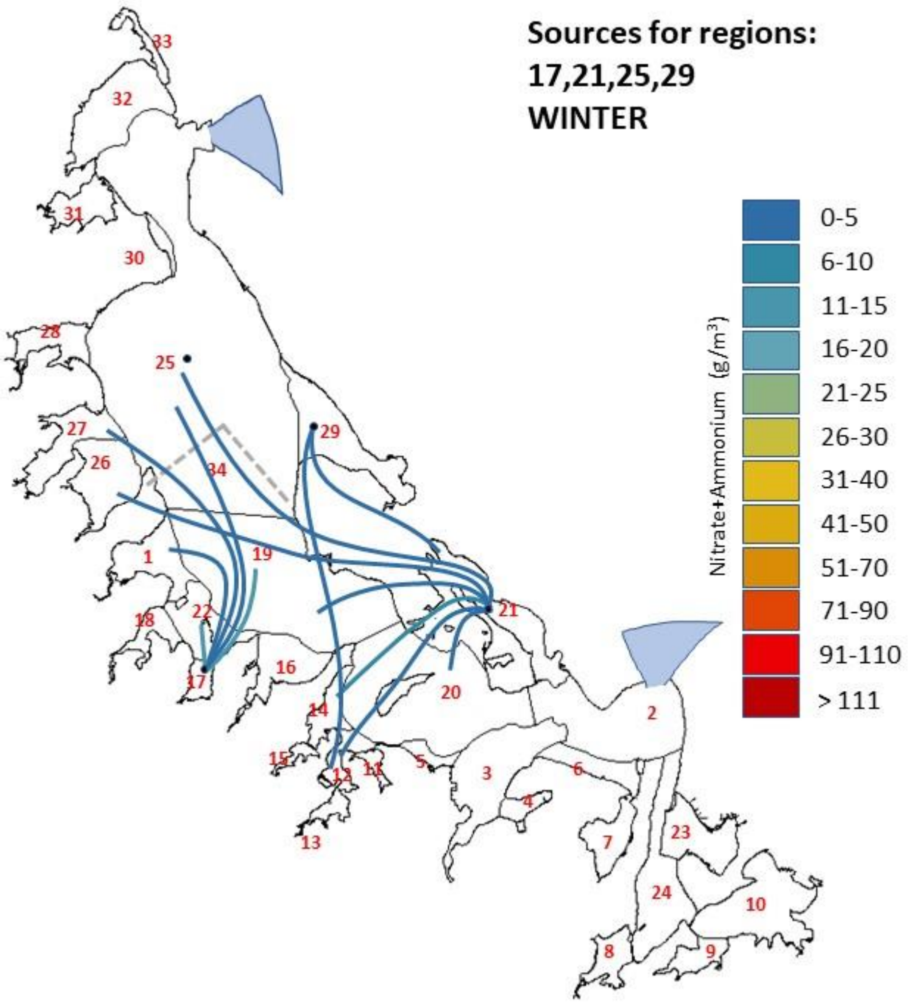


***Figure A47**: Net sources/sinks of nitrate and ammonium for regions 17,21,25,29 for winter. See Figure A44 for an explanation.*

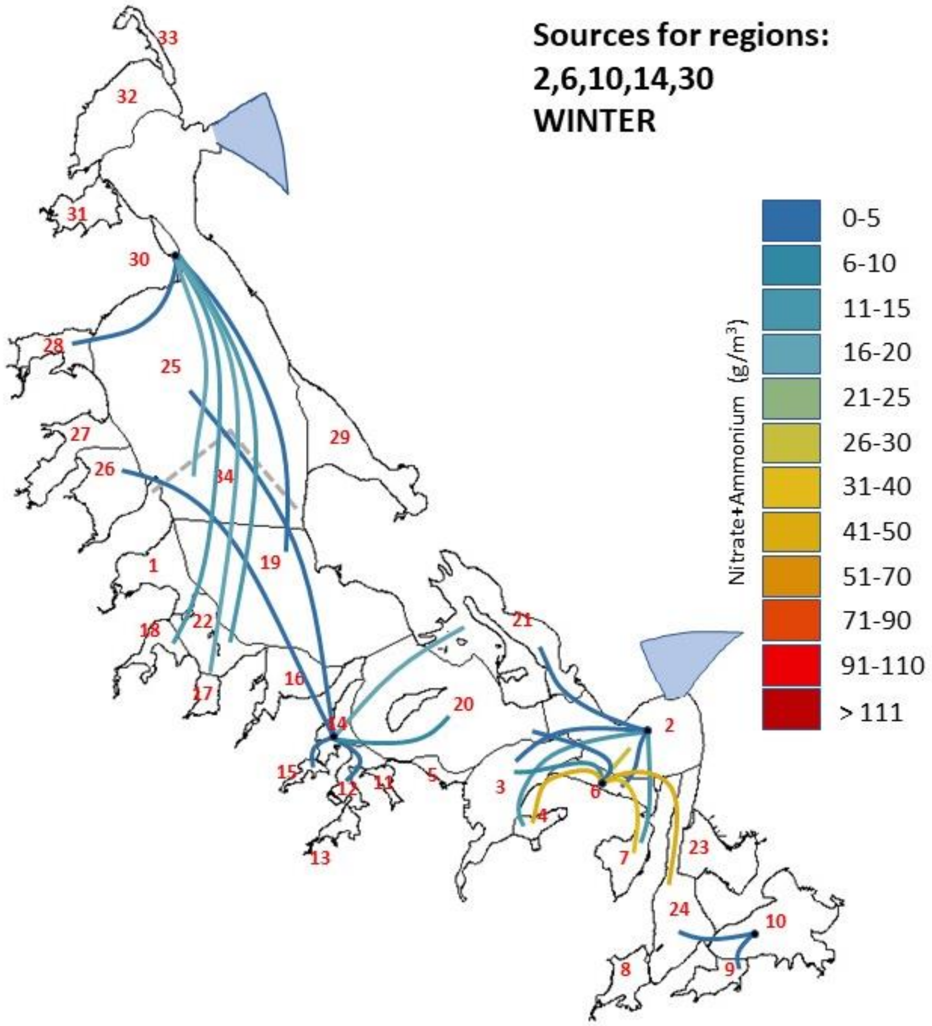


***Figure A48**: Net sources/sinks of nitrate and ammonium for regions 2,6,10,14,30 for winter. See Figure A44 for an explanation.*

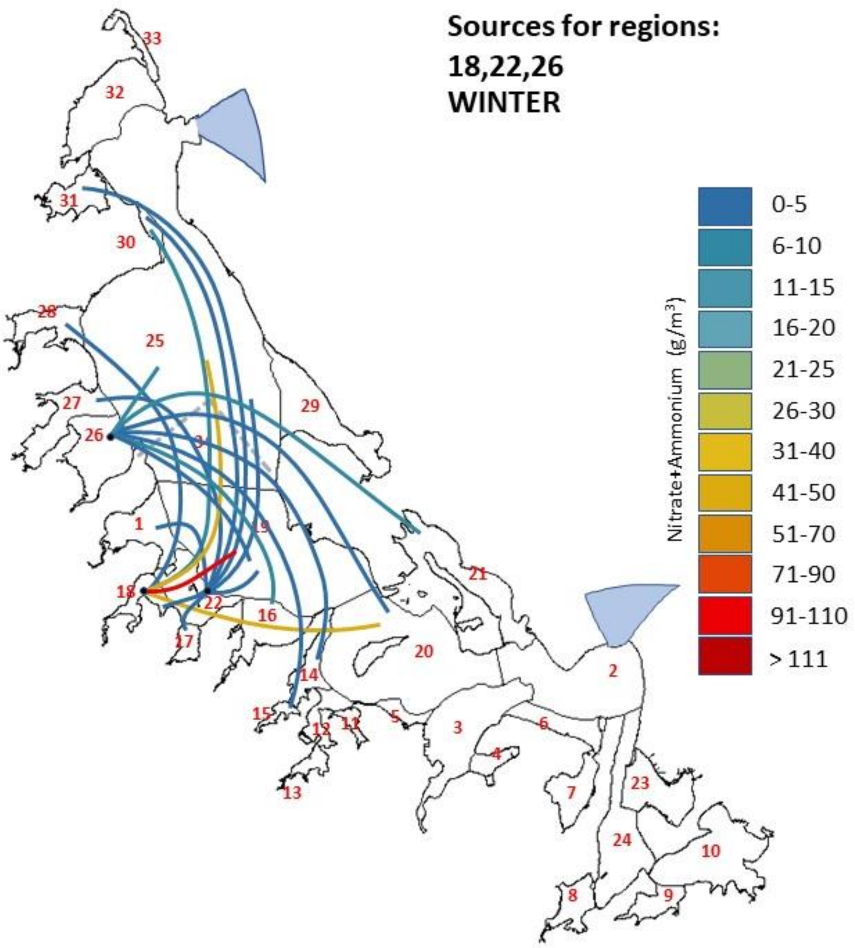


Figure A49*: Net sources/sinks of nitrate and ammonium for regions 18,22,26 for winter. See Figure A44 for an explanation.*

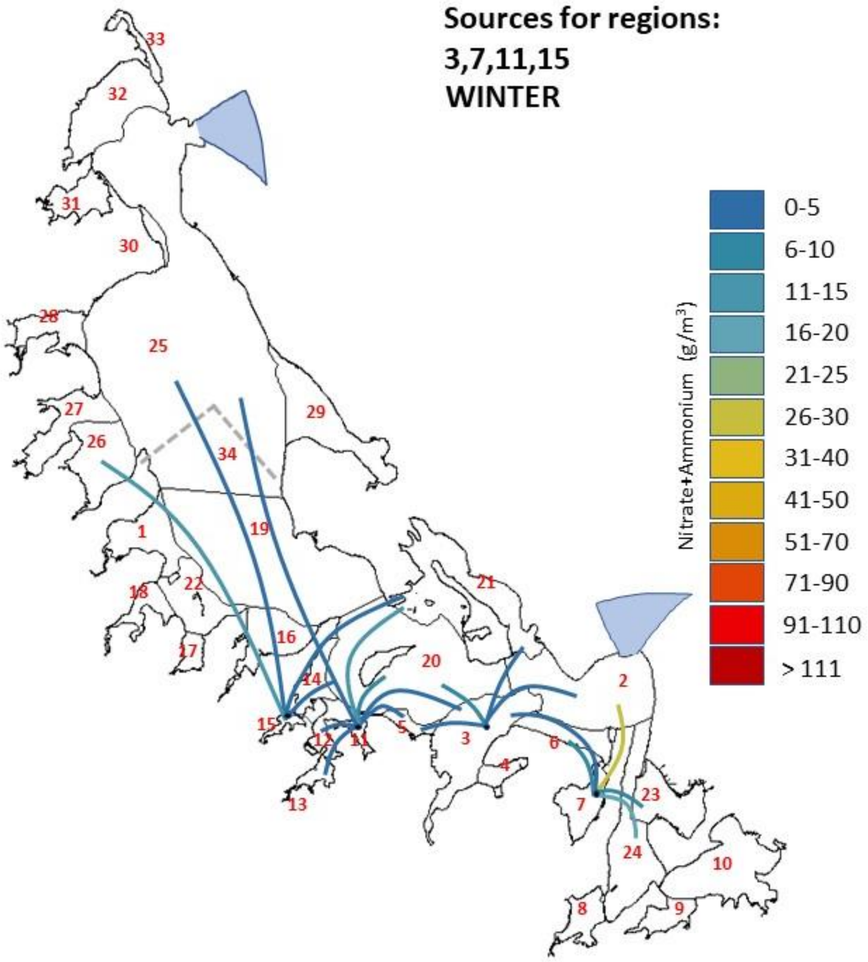


Figure A50: *Net sources/sinks of nitrate and ammonium for regions 3,7,11,15 for winter. See Figure A44 for an explanation.*

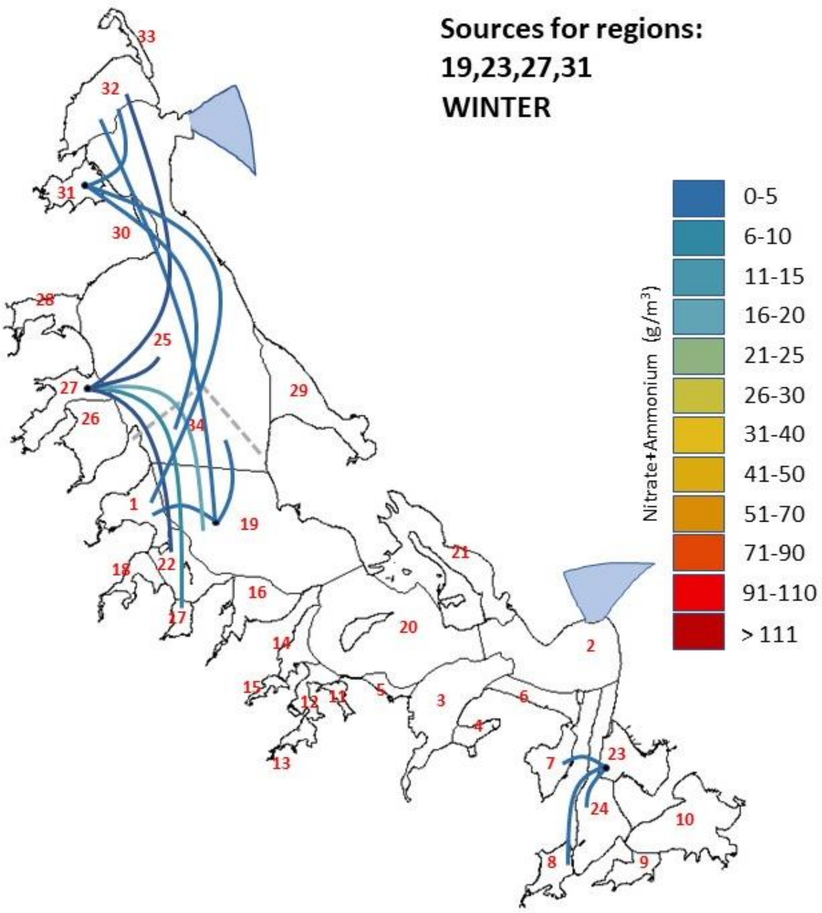


***Figure A51**: Net sources/sinks of nitrate and ammonium for regions 19,23,27,31 for winter. See Figure A44 for an explanation.*

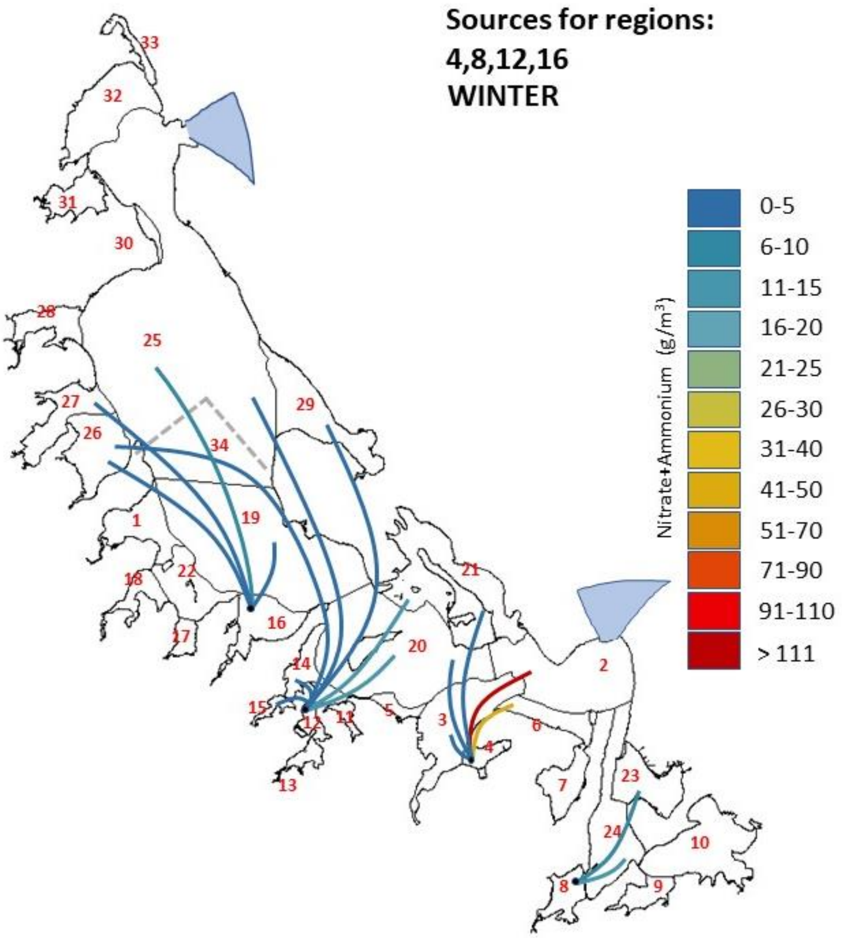


***Figure A52**: Net sources/sinks of nitrate and ammonium for regions 4,8,12,16 for winter. See Figure A44 for an explanation.*

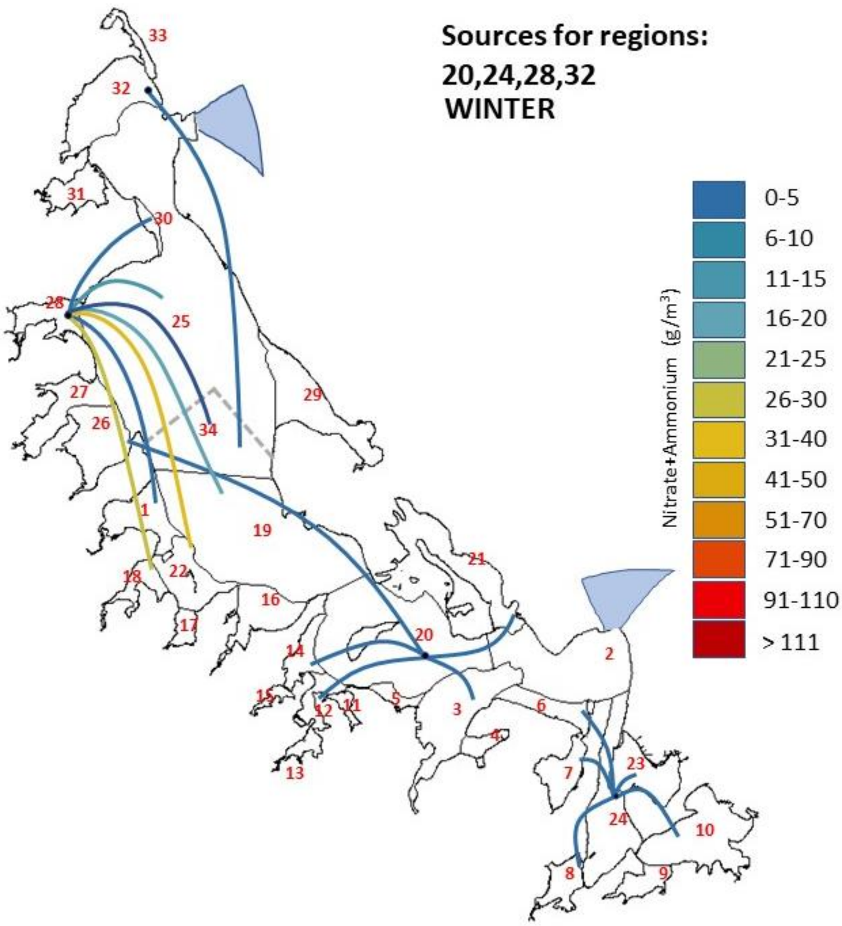


Figure A53*: Net sources/sinks of nitrate and ammonium for regions 20,24,28,32 for winter. See Figure A44 for an explanation.*

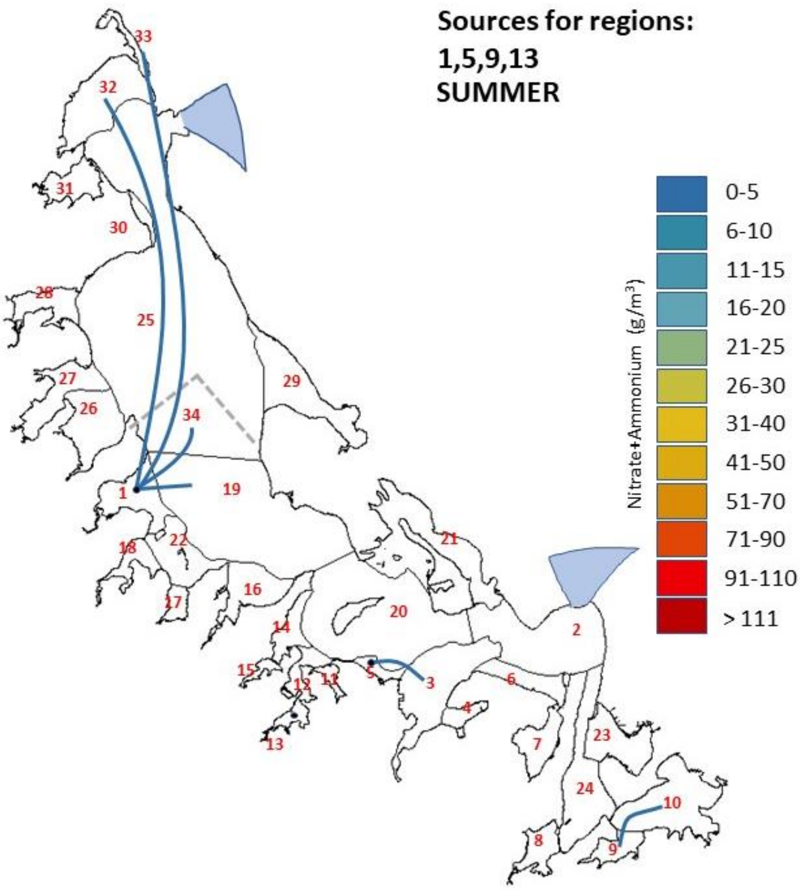


***Figure A54**: Net sources/sinks of nitrate and ammonium for regions 1,5,9,13 for summer. See Figure A44 for an explanation.*

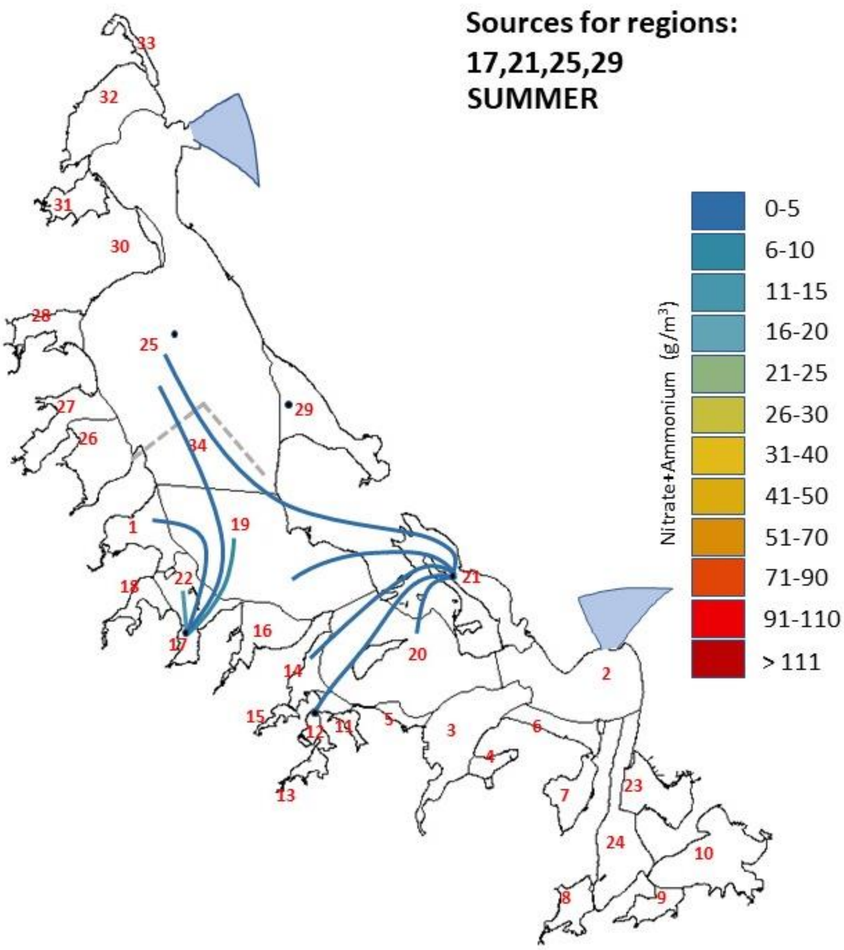


Figure A55*: Net sources/sinks of nitrate and ammonium for regions 17,21,25,29 for summer. See Figure A44 for an explanation.*

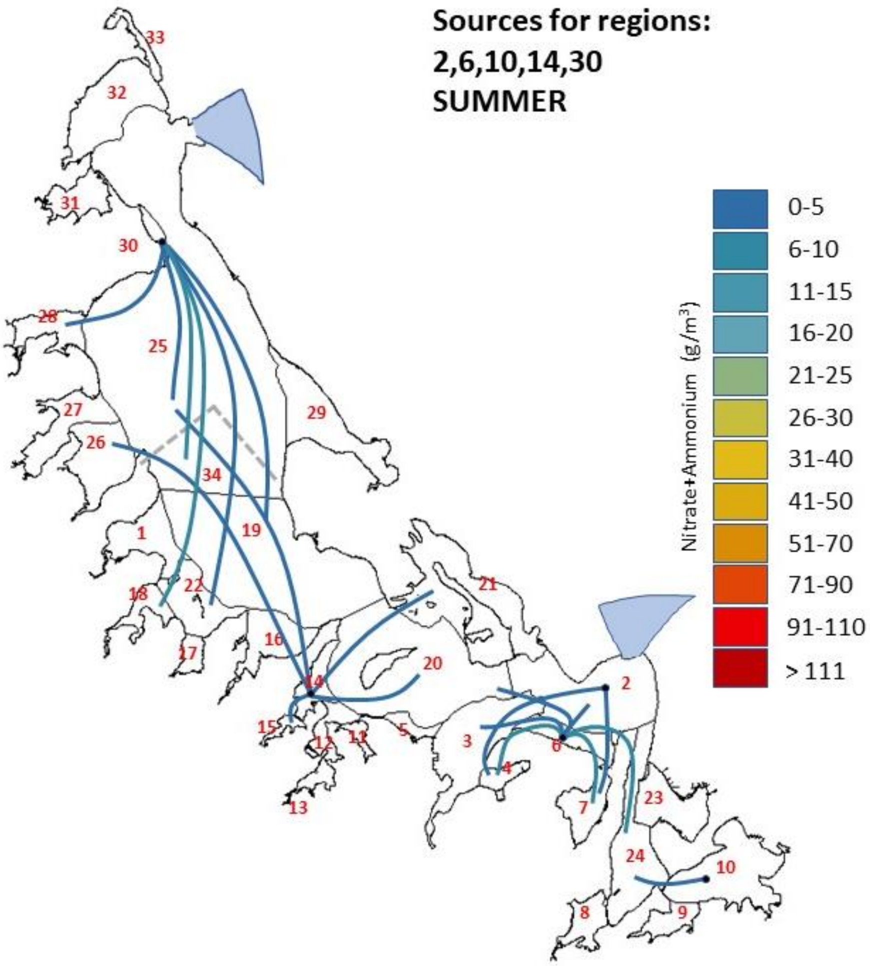


***Figure A56**: Net sources/sinks of nitrate and ammonium for regions 2,6,10,14,30 for summer. See Figure A44 for an explanation.*

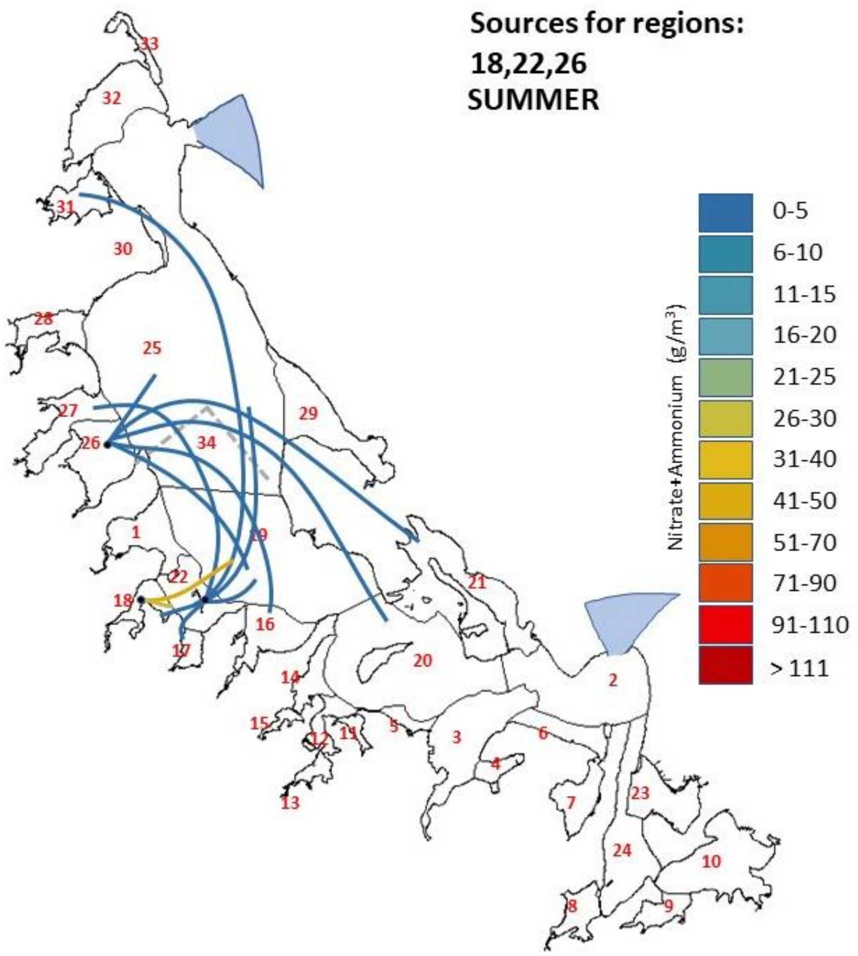


Figure A57*: Net sources/sinks of nitrate and ammonium for regions 18,22,26 for summer. See Figure A44 for an explanation.*

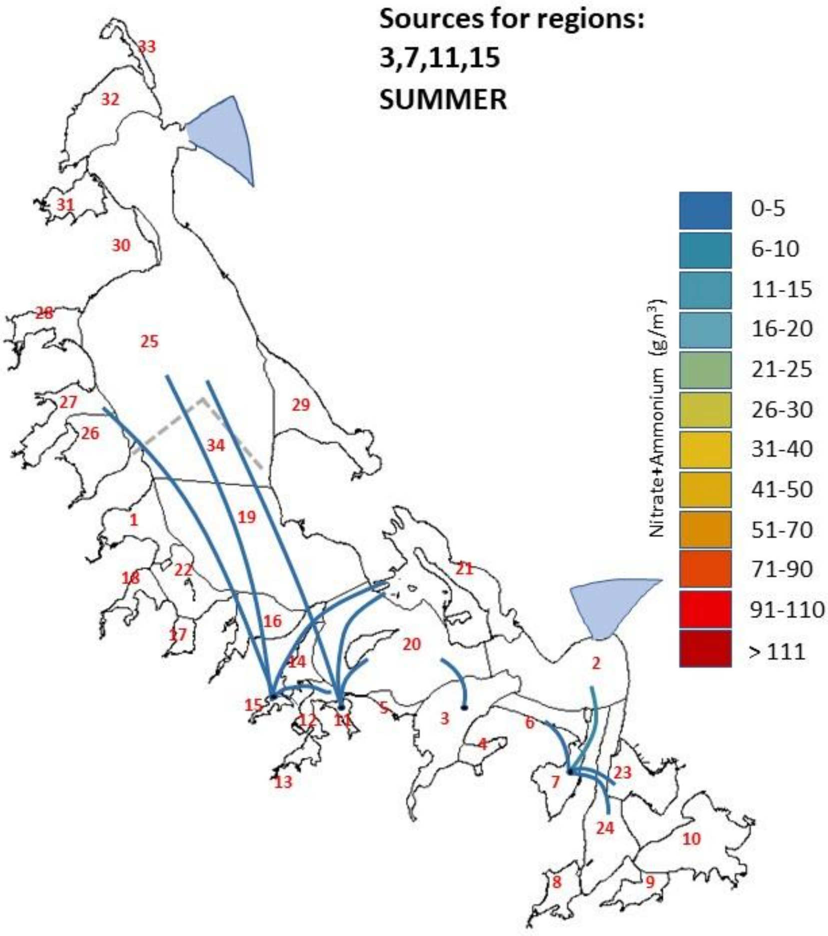


Figure A58: *Net sources/sinks of nitrate and ammonium for regions 3,7,11,15 for summer. See Figure A44 for an explanation.*

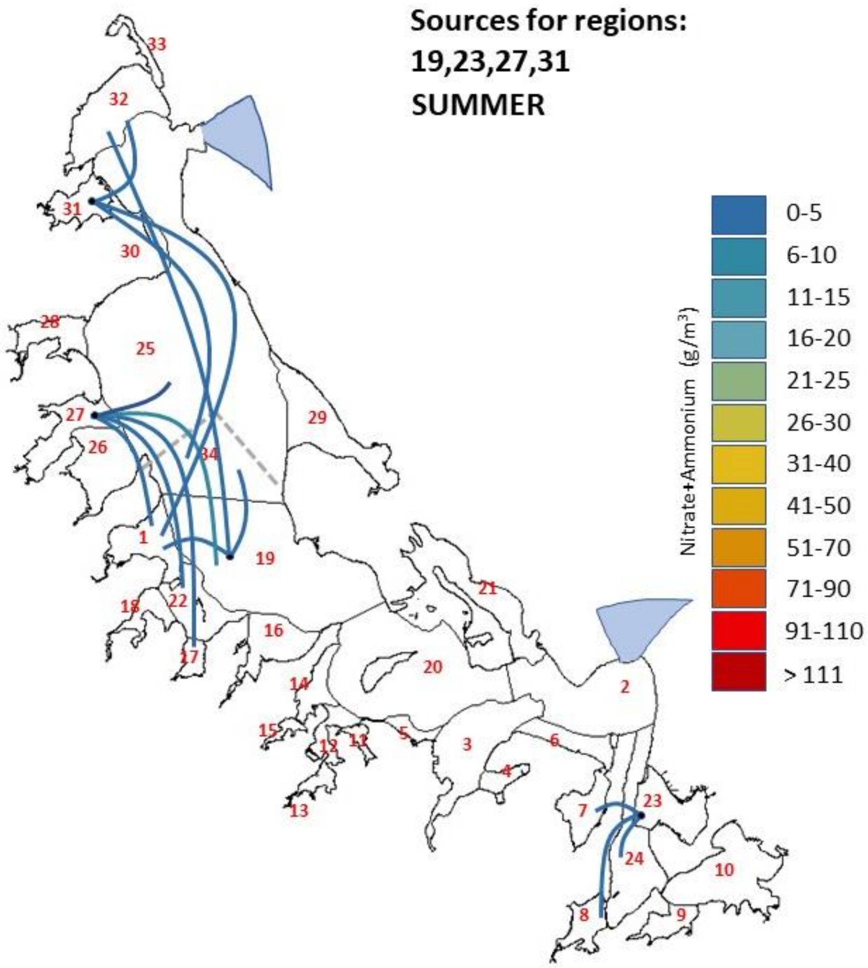


Figure A59: *Net sources/sinks of nitrate and ammonium for regions 19,23,27,31 for summer. See Figure A44 for an explanation.*

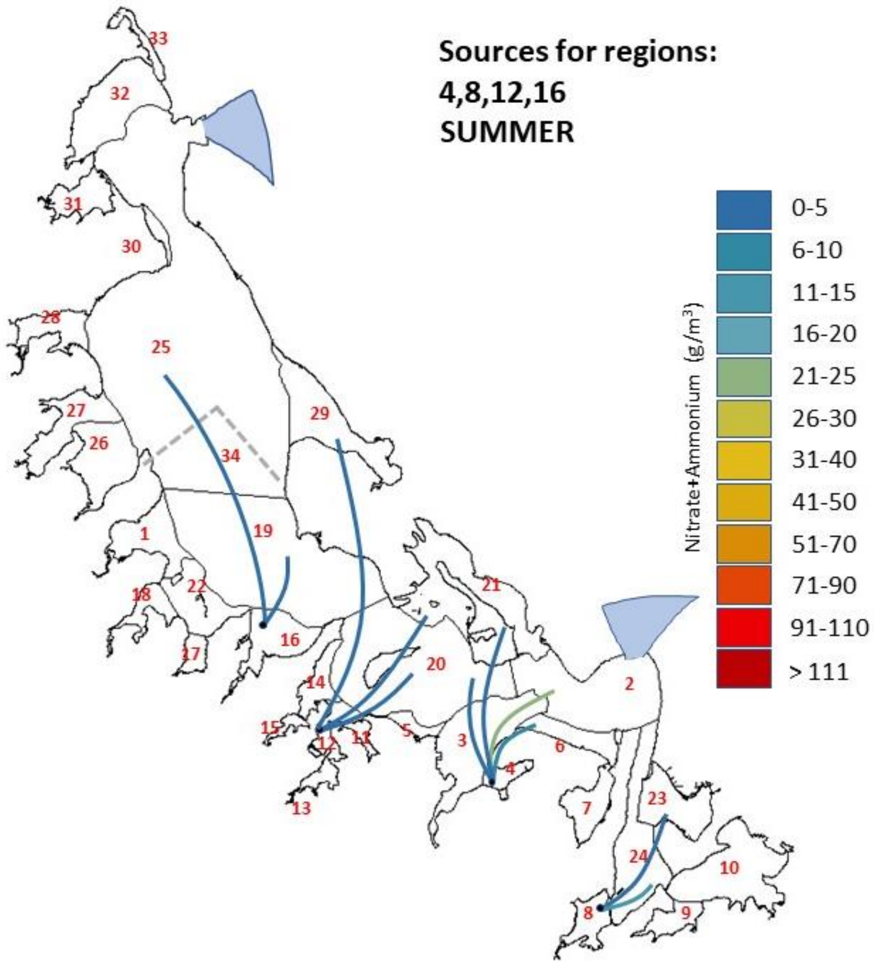


Figure A60: *Net sources/sinks of nitrate and ammonium for regions 4,8,12,16 for summer. See Figure A44 for an explanation.*

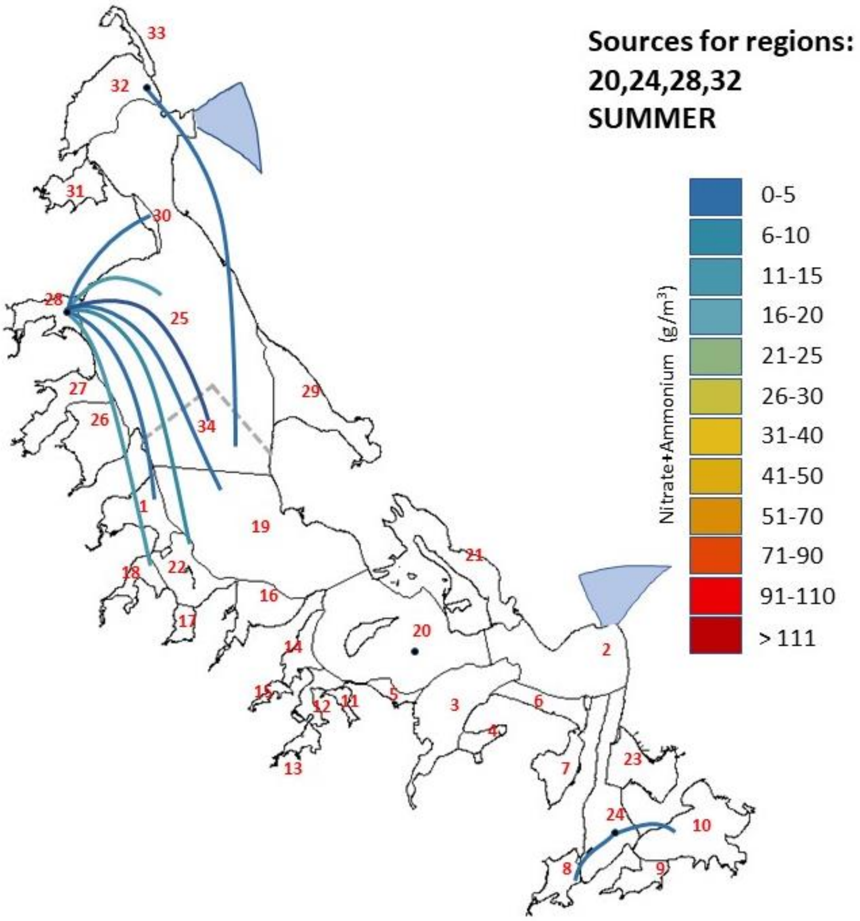


Figure A61: *Net sources/sinks of nitrate and ammonium for regions 20,24,28,32 for summer. See Figure A44 for an explanation.*

Appendix 7: Summary of Physical Characteristics of the Harbour by Region

TableA1: Table of physical characteristics needed for the Estuarine Trophic Index Tool 1. The ID numbers refer to the locations provided in Appendix 1

ESTUARY SUB REGIONS	ID	LAT	LON	Salinity (ppt)	Intertidal Area (%)	Intertidal volume (%)	Model grid area (grid cells) MHWS	Mean depth MHWS (m)	Tidal Height (m)	Volume (m^3)	Tidal Prism (m^3)
Aongatete Estuary	1	-37.600884	175.9733	27.26	100.0	100.00	3.08E+06	0.68	1.75	2.08E+06	2.08E+06
Blue Gum Bay		-37.564611	176.0439	32.64	98.9	99.88	5.91E+06	0.91	1.75	5.37E+06	5.36E+06
Hunters Creek	21	-37.619721	176.115	32.64	91.3	97.84	8.03E+06	1	1.75	8.09E+06	7.91E+06
Lower Estuary	2	-37.650228	176.1562	33.78	1.3	28.32	1.04E+07	6.1	1.75	6.45E+07	1.83E+07
Mangawhai Estuary 1	14	-37.649936	176.0427	31.55	79.5	91.79	1.76E+06	1.09	1.75	1.92E+06	1.76E+06
Mangawhai Estuary 2	15	-37.660743	176.0326	26.81	100.0	100.00	7.13E+04	0.03	1.75	2.32E+03	2.32E+03
Matahui west	26	-37.582308	175.9556	27.26	98.6	99.88	4.52E+06	1	1.75	4.53E+06	4.52E+06
Middle Estuary	20	-37.642902	176.0868	32.27	6.3	46.21	1.74E+07	3.86	1.75	6.73E+07	3.11E+07
North Estuary	25	-37.524548	175.9898	32.42	40.0	62.56	5.72E+07	2.4	1.75	1.39E+08	8.71E+07
Ongare	30	-37.506021	175.9735	32.42	51.3	84.01	6.03E+05	1.85	1.75	1.12E+06	9.37E+05
Otumoetai	6	-37.662201	176.1454	32.48	57.9	82.44	2.14E+06	1.87	1.75	3.98E+06	3.28E+06
Rangataua Bay	10	-37.70664	176.2112	28.13	76.2	94.82	6.72E+06	1.33	1.75	8.91E+06	8.44E+06
Rereatukahia Estuary	27	-37.565936	175.9397	23.35	92.4	98.79	3.33E+06	1.09	1.75	3.63E+06	3.59E+06
Southern Estuary	24	-37.694666	176.1723	30.78	40.2	47.98	6.08E+06	3.31	1.75	2.01E+07	9.64E+06
Te Puna Beach	5	-37.660016	176.0793	32.13	64.2	81.80	7.90E+05	1.74	1.75	1.38E+06	1.13E+06
Te Puna Estuary 1	12	-37.663004	176.0468	31.33	71.2	89.47	1.33E+06	1.4	1.75	1.86E+06	1.67E+06
Te Puna Estuary 2	13	-37.677219	176.047	28.86	100.0	100.00	5.17E+05	0.84	1.75	4.34E+05	4.34E+05
Tuapiro Athenree	32	-37.462546	175.9568	32.15	91.1	95.30	6.34E+06	1.07	1.75	6.77E+06	6.45E+06
Tuapiro Estuary	31	-37.494579	175.9435	25.12	97.6	99.11	2.03E+06	0.92	1.75	1.87E+06	1.85E+06
Upper Estuary	19	-37.61122	176.0293	31.05	42.3	75.23	2.24E+07	2.11	1.75	4.73E+07	3.56E+07
Uretara Estuary	28	-37.534351	175.933	27.26	98.8	99.94	1.83E+06	1.03	1.75	1.90E+06	1.89E+06
Waiau Estuary	33	-37.441661	175.9649	32.15	100.0	100.00	5.93E+05	0.59	1.75	3.51E+05	3.51E+05
Waikaraka Estuary	11	-37.662553	176.0616	30.48	100.0	100.00	3.67E+05	0.42	1.75	1.54E+05	1.54E+05
Waikareao Estuary	7	-37.682528	176.1572	25.12	93.2	97.49	2.29E+06	1.07	1.75	2.44E+06	2.38E+06
Waimapu Estuary	8	-37.719287	176.1591	23.35	100.0	100.00	1.49E+06	1	1.75	1.50E+06	1.50E+06
Wainui Estuary 1	22	-37.619866	175.992	30.25	94.5	98.64	3.46E+06	0.95	1.75	3.28E+06	3.23E+06
Wainui Estuary 2	17	-37.637177	175.994	28.36	100.0	100.00	5.74E+05	0.54	1.75	3.07E+05	3.07E+05
(Apata) Wainui Estuary 3	18	-37.623451	175.9742	27.24	100.0	100.00	1.14E+06	0.64	1.75	7.29E+05	7.29E+05
Waipapa Estuary	16	-37.634986	176.0236	30.20	78.6	94.65	3.40E+06	1.28	1.75	4.35E+06	4.11E+06
Waipu Bay	23	-37.682958	176.1874	32.15	88.4	96.45	3.68E+06	1.15	1.75	4.24E+06	4.09E+06
Wairoa Estuary 1	3	-37.66514	176.1094	21.79	62.6	94.91	7.31E+06	1.48	1.75	1.08E+07	1.03E+07
Wairoa Estuary 2	4	-37.676523	176.1178	19.03	100.0	100.00	6.17E+05	0.69	1.75	4.29E+05	4.29E+05
Welcome Bay	9	-37.720765	176.1905	29.49	100.0	100.00	1.34E+06	0.88	1.75	1.18E+06	1.18E+06