Hauraki Integrated Land-Water Model

Pilot modelling and strategy

Prepared for Ministry for Business Innovation and Employment

August 2021

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NIWA CLIENT REPORT No: 2021171HN
Report date: August 2021
NIWA Project: FWNC2109

Quality Assurance Statement		
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	Approved for release by:	Scott Larned

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Executive summary

This report documents the outcomes from the first year of a multi-year programme intended to couple land and marine models to address water quality and associated ecological issues, for integrated freshwater-marine limit-setting, and to address related resource management needs. The focus of the study is on the Hauraki Gulf/Tīkapa Moana and its catchment and streams, but the coupled modelling approach is expected to have applicability to a range of systems in New Zealand.

Key components of the first year of the project documented in this report include:

A. **A pilot modelling exercise coupling selected models** for catchment hydrology, generation of contaminant loads, and eutrophication response in the Gulf. The coupled models were applied to illustrative scenarios of source load reduction and climate change.

B. **Preparation of a broad strategy and work plan** for future integrated modelling and associated data collection for the Hauraki Gulf. This involved developing a well-deliberated strategy and a modular design for coupled freshwater-marine modelling, developing an associated data collection programme, and documenting a future work programme. The strategy design included consideration of the range of technical and information needs to address priorities of the Waikato Regional Council and Auckland Council. These needs were in part identified in a workshop.

The pilot modelling study demonstrated the feasibility of linking catchment and coastal models to predict coastal eutrophication responses over a decadal timescale, and the application of the models to investigate the marine implications of freshwater nitrogen limits.

Application of the coupled models revealed the need for improvements, refinements and additions of individual models; these changes have been incorporated into the work plan. For example, it is recommended that:

- catchment modelling is transitioned to SWAT,
- models for benthic enrichment are developed to enable better quantification of benthic state and nutrient flux, including long-term changes in benthic composition and benthic-water exchange,
- dissolved oxygen models for streams and rivers are added,
- a benthic health model is added, and
- a mitigation economics model is added.

Iwi liaison has been initiated at the 'inform' level, but it is anticipated that there will be deeper engagement in the future.

Most of the required data collection is underway or will be undertaken by Regional Councils or NIWA. An exception is a survey of benthic health to inform the development of a benthic health model, for which resourcing is still to be identified.

An ambitious programme for model development is proposed to address high-priority needs, including application of models in an integrated land-water limit-setting that accounts for both freshwater and marine effects. Several opportunities to expand the scope of work beyond the proposed programme have also been identified.

1 Introduction

The Inner Hauraki Gulf/Tīkapa Moana ecosystem is degraded, facing proliferations of algae, de-oxygenation, reduced pH (acidification), reduced water clarity, and muddier sediments arising from historical land-derived contaminant inputs. These effects are likely to be exacerbated by continued inputs and climate change. Freshwater systems feeding the Gulf, such as those in the Hauraki Plains, also face stressors such as deoxygenation and excessive macrophyte growth. Regional planning initiatives have called for predictive integrative models to help identify contaminant load limits for the Hauraki Gulf land-freshwater-marine system. These models need to incorporate the effects of climate change and mitigation systems used to reduce contaminant loads.

To address these management needs, we envisage a set of coupled models that will ultimately link:

- land generation of contaminants (primarily sediment and nutrients), including load reductions from and cost of mitigation measures
- river transport, nutrient concentrations, and eutrophication (including dissolved oxygen depletion), in tributaries, the main stem, and lower tidal reaches of the main rivers
- nutrient transport, sediment transport and deposition, primary production, pH and de-oxygenation and associated biological impacts in the Hauraki Gulf.

Key questions that could be addressed by such a system include:

- By how much do nutrient loads need to be reduced to reduce risks of adverse environmental effects on the coastal marine system?
- When and where do adverse effects occur in the Gulf? What is the role of benthic storage of nutrients?
- How much do loads need to be reduce by to achieve freshwater nutrient-related objectives?
- What are the risks associated with climate change?
- What are the risks for de-oxygenation of stream and river waters, and will nutrient reductions or other mitigation measures decrease the risks?
- Which is more sensitive: the marine or freshwater sub-system? Will managing for impacts on one sub-system ensure that the other sub-system is protected?
- What needs to be done on the land to achieve the reductions (i.e., where in the catchment and to what extent should land use change occur to achieve the decrease in contaminant load required), and how much would it cost?

While NIWA and other research organisations have freshwater and marine models that can be used to address some of these information needs, there is a need to organise, integrate, and extend the capability of models in a structured way, and to present findings in ways that are useful to decision-makers.

While there are some existing models for parts of the Hauraki system, there are gaps in coverage and capability, and the models need to be integrated to represent the full extent of land-sea interactions. Existing data sources are likely to be insufficient to train and test the models, so new data will need to be collected in a targeted way.

We envisage that a large integrated programme of applied research will be required to address these pressing environmental concerns, and to develop appropriate management tools and environmental models. The scope of modelling activities will need to be extended to address economic, social and keystone species aspects. Some models will already be available, while others will need to be developed to fill critical gaps. It is expected that Waikato Regional Council and Auckland Council will collaborate in this large NIWA-led project, and that the proposal will be an excellent candidate for MBIE Endeavour Programme funding or similar. It is likely that Hauraki Iwi will also have a strong interest in this work.

The integrated catchment-land modelling approach is likely to be applicable to systems beyond the Hauraki Gulf, and to a broader set of applications including load limit-setting. So, the work in the current project is intended to develop a general, transferable approach that can be adopted in other locations. The proposed project aligns with NIWA's strategic goal of integrated research across the Freshwater and Estuaries and Coasts and Oceans Centres. The project will bring together and draw upon expertise and models developed in both Centres.

The work described in this report relates to the first year of the project. The work for the first year was centred around two key components:

A. **A pilot modelling exercise coupling selected existing models** for catchment hydrology, generation of contaminant loads, and eutrophication response in the Gulf, including application of a scenario for source load reduction to meet freshwater objectives, and a single climate change scenario. The model components, which are described in more detail in the report, included:

- TopNet, a national hydrologic model for New Zealand, which provided daily flow predictions for all river segments in the catchment. This was driven by daily climate from either:
  - the VCSN, a spatial interpolation of historical climate observations, in this case including observations by the Regional Councils or
  - climate predictions from regionally downscaled global circulation models.
- CLUES, a national model which provided predictions of mean annual nitrogen loads for all river segments in the catchment. Estimates of daily loading were made by applying rating-curve methods (basically, relationships between flow and concentration) to the flow time-series from TopNet. To provide a ‘best estimate’ of historical loading, use was also made of the WRTDS-K model, which interpolates observed concentration time-series to give daily predictions.
- SWAT, a dynamic catchment model which operates on a daily basis, was used to estimate the change in mean annual load under a climate change scenario.

- ROMS, an ocean hydrodynamics model with associated biogeochemical models NZPD and Carbon Chemistry model, which was used to predict eutrophication responses of the gulf to catchment and other nitrogen inputs over a decadal timescale.

B. **Preparation of a broad strategy and work plan** for future integrated modelling and associated data collection for the Hauraki Gulf. This involved developing a well-deliberated strategy and modular design for coupled freshwater-marine modelling, developing an associated data collection programme, and documenting a future work programme. This included consideration of the range of technical and information needs that to address priorities of the Waikato Regional Council and Auckland Council. The modular system identifies a set of models and components, supporting data, coupling mechanisms, delivery mechanisms, and visualisation to meet prioritised information needs, both for immediate planning purposes and to build system understanding. This aspect of the project also entailed initial liaison with Iwi to inform them of the project, to begin identifying and documenting their needs, and to identify opportunities for Iwi-led components of a future programme.

2 Pilot modelling study methods

2.1 Study area and spatial arrangement

The extent of the modelled catchment area is shown in Figure 2-1. The key area of interest in the marine zone extends between the northernmost points of the modelled catchment area (Hauraki Gulf, between Takatu Point (Tāwharanui Peninsula) and Cape Colville), but the extent of the modelled ocean area (Figure 2-2) goes beyond the Gulf to include the Inner Shelf area.

Figure 2-1: Extent of the modelled catchment area (shaded in yellow). Blue lines indicate the stream network.

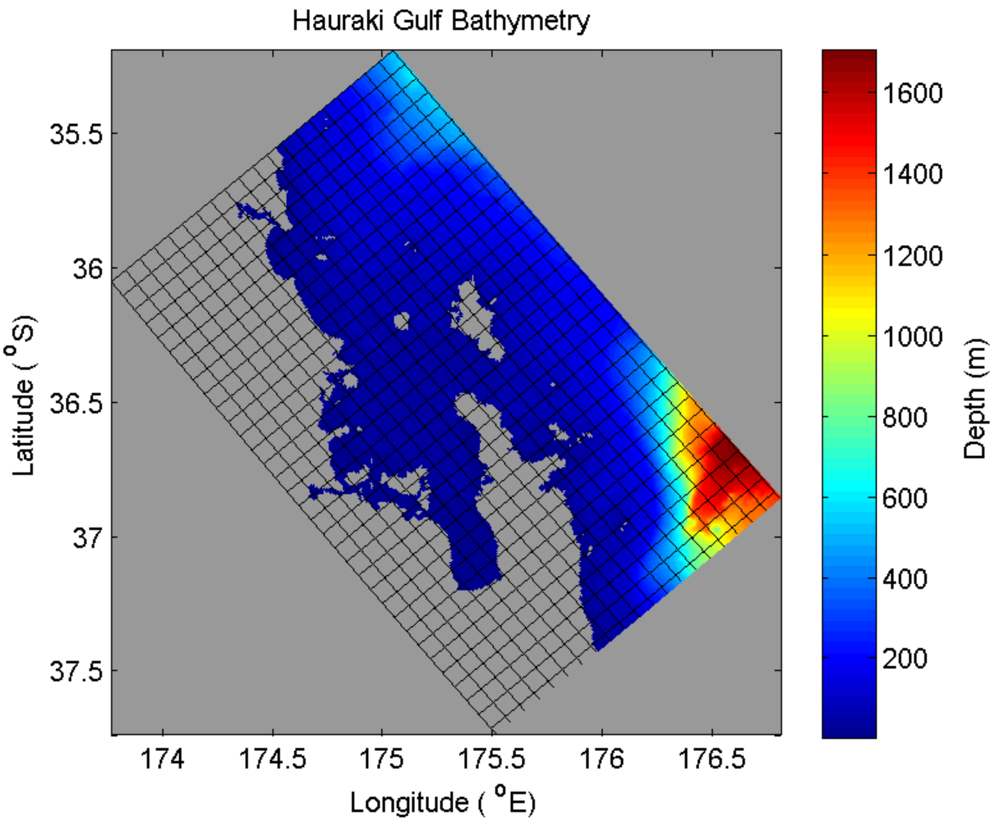


Figure 2-2: The ROMS coastal modelling domain. The black lines indicate every 10th model grid cell (each cell is 750 m square), and the shading shows model depth.

The area of the modelled catchment is 5858 km^2. The stream network was based on the River Environment Classification (REC, Snelder et al. 2010) version 2.5, with 12800 sub catchments. There were 721 terminal locations (where streams or rivers flow into the sea).

2.2 Overview of models used and their interlinkage

This project applied the following models, which are described in more detail later in the report:

- TopNet, a national hydrologic model for New Zealand, which provided daily flow predictions for all river segments in the catchment. This was driven by daily climate from either a) VCSN, a spatially-interpolation of historical climate observations, in this case including observations by the Regional Councils, or b) climate predictions from regionally downscaled global circulation models.

- CLUES[1], a national model which provided predictions of mean annual nitrogen loads for all river segments in the catchment. Estimates of daily loading were made by applying rating-curve methods (basically, relationships between flow and concentration) to the flow time-series from TopNet. To provide a 'best estimate' of historical loading, use was also made of the WRTDS-K model, which interpolates observed concentration time-series to give daily predictions.

[1] CLUES uses other models (OVERSEER and SPASMO) to estimate losses from land use - https://niwa.co.nz/freshwater-and-estuaries/our-services/catchment-modelling/clues-catchment-land-use-for-environmental-sustainability-model

- SWAT, a dynamic catchment model which operates on a daily basis and was used to estimate the change in mean annual load under a climate change scenario.
- ROMS, an ocean hydrodynamics model with associated biogeochemical models NZPD and Carbon Chemistry model, which was used to predict eutrophication responses of the gulf to catchment and other nitrogen inputs over a decadal timescale.

The inter-relation between these models is shown schematically in Figure 2-3. Data were generally exchanged between models using time-series for relevant river segments in NetCDF format. An exception was for SWAT, where only changes in mean annual load were provided to modify the CLUES mean annual loads.

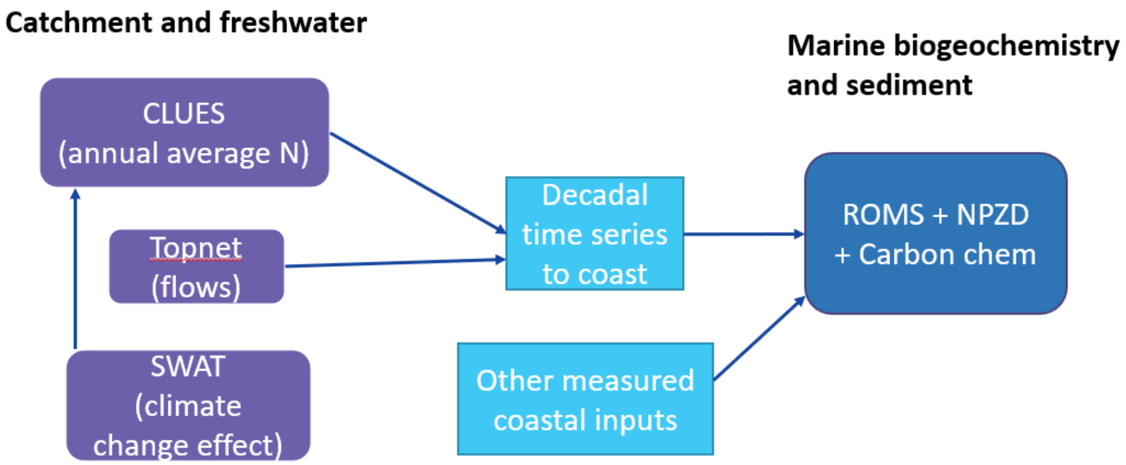


Figure 2-3: Key model components and their inter-relationships.

2.3 Scenarios considered

To demonstrate the use of the coupled models in scenario analysis, the following scenarios were investigated to provide inputs to the coast:

- **Load reduction**. This involved applying nitrogen load reductions to meet freshwater bottom-line limits (if they are not currently met) for nitrate toxicity and TN (total nitrogen) in relation to periphyton abundance. Additionally, an ecosystem health limit of 1 mg/L of DIN (dissolved inorganic nitrogen) was applied. The methodology followed that used in previous work for MfE and is described further in Section 2.5.9.
- **Climate Change**. A single future climate change scenario was applied to provide predictions over the period 2050-2059. Climate drivers were based on the RCP8.5 emissions scenario (a business-as-usual scenario) from regionally downscaled predictions from the HadGEM2-ES climate model. The climate models were based on CMIP5 (Phase 5 of the Climate Change Intercomparison Project which was used in the IPCC Fifth Assessment Report). Changes in mean annual loading were estimated from an application of the SWAT dynamic model to a small catchment using the climate model predictions, resulting in an estimate of percentage change in load due to climate change. The percentage was then applied to estimates of the current mean annual load derived from the CLUES model to predict likely future catchment loads. Changes in flow were estimated with the TopNet hydrologic model. The time series of

load was then determined by applying rating-curve methods to the predicted flows, with scaling of concentrations to achieve the target mean annual load.

Additionally, two baseline scenarios were used:

- **Baseline 1**. This is the 'best estimate' of historical loading over the period 2009-2019, making use of a) measurements where and when available and b) the CLUES catchment model for mean annual loads in conjunction with TopNet simulated flows using VCSN drivers for locations where nearby measurements were not available.
- **Baseline 2**. This was for the period 2009-2019 but used the same methods as for the Climate Change scenario, except: a) used climate model predictions over the historical period; and b) mean annual load was not changed from the CLUES baseline value. This scenario was used to compare with the Climate Change predictions for the future, to avoid bias that might otherwise be associated from switching from measured to modelled climate (due to, for example, frequencies of runoff events or durations of dry spells that could be different between measured and modelled climate).

2.4 Hydrologic model (TopNet)

The NZWaM surface water model, or TopNet hydrological model, is routinely used for hydrological modelling applications in New Zealand. It is a spatially distributed, time-stepping model of water balance. It is driven by time series of precipitation and temperature data, using additional climate elements where available. TopNet simulates water storage in the snowpack, plant canopy, rooting zone, shallow subsurface, lakes and rivers. It produces time series of modelled river flow (under natural conditions) throughout the modelled river network, as well as evaporation time series. TopNet has two major components, namely a basin module and a flow routing module. The structure of the basin module is illustrated in Figure 2-4.

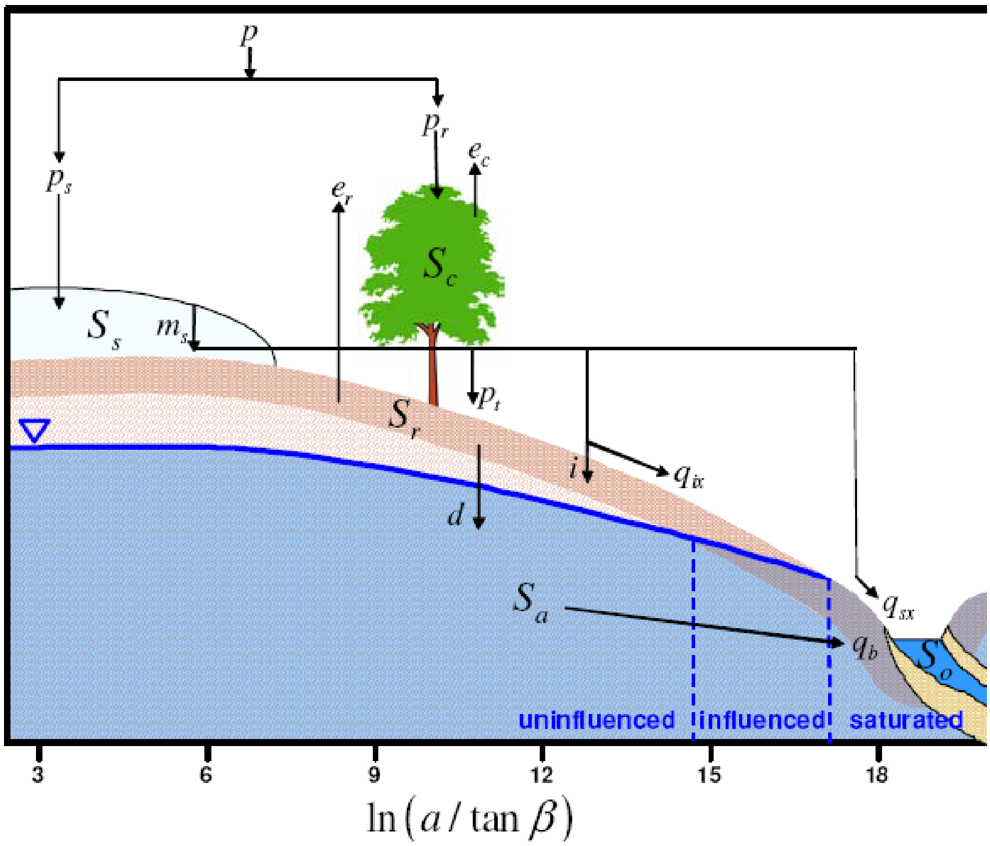


Figure 2-4: TopNet model structure within each sub-basin, showing modelled water fluxes and storages (Clark et al. 2008).

The model combines TOPMODEL hydrological model concepts (Beven et al. 1995) with a kinematic wave channel routing algorithm (Goring 1994; Clark et al. 2008) and a simple temperature based empirical snow model (Clark et al. 2008). As a result, TopNet can be applied across a range of temporal and spatial scales over large catchments using smaller sub-basins as model elements (Ibbitt and Woods 2002; Bandaragoda et al. 2004). Considerable effort has been made during the development of TopNet to ensure that the model has a strong physical basis and that the dominant rainfall-runoff dynamics are adequately represented in the model (McMillan et al. 2010). TopNet model equations and information requirements are provided by Clark et al. (2008) and McMillan et al. (2013).

The TopNet model is built on two fundamental assumptions:

- Any groundwater flux generated within a representative unit has to discharge within that unit. As a result, the TopNet model contains a simple groundwater model (associated with linear reservoir conceptualisation) but does not allow transfer of groundwater fluxes between catchments.
- Hydrological processes over the catchment are directly associated with the notion of "catchment average depth to groundwater". This enables a surface water catchment to be defined in three distinctive (but time varying) areas:
  - **saturated zone** where the groundwater is close to the surface and interacts with vadose zone processes (e.g., riparian zone where groundwater is usually "connected" to the vadose zone),

- the **influenced zone** where the groundwater is relatively close to the surface and could interact with vadose zone processes under large rainfall events, and
- the **uninfluenced zone** where the catchment average depth to groundwater is relatively deep and is not connected to or influencing vadose zone processes.

Spatial information in TopNet is provided by national datasets covering:

- Catchment topography (i.e., national 30 m resolution digital elevation model) (Newsome et al. 2012).
- Land Cover Database version 4-LCDB4 and Land Resource Inventory (Newsome et al. 2012).
- Fundamental Soil Layer - FSL (Wilson and Giltrap 1982).
- Hydrological properties (REC, Snelder et al. 2010).

In this application, the Digital River Network (DN) hydrological network was set to version 2 (Snelder et al. 2010). The method for deriving TopNet initial parameter estimates from GIS data sources in New Zealand is given in Table 1 of Clark et al. (2008).

2.5 Contaminant source models

2.5.1 WRTDS daily load estimation from measurements

As part of estimating historical daily nitrogen loading into the Gulf, the measured concentration records at key monitoring sites were interpolated over the period of record. The model WRTDS (Weighted Residuals of Time Discharge and Season) from the USGS was used (Hirsch and De Cicco 2015; Lee et al. 2019). WRTDS calculates loads by estimating concentrations over time from measured values and a fitted regression model; is not a predictive catchment model. The method works by fitting a local weighted regression at each point in an evenly spaced discharge-time grid. At each point the local regression equation for logged concentration is a linear function of flow, time of year, and season, and is weighted more for observations closest to the grid point. Predictions of concentration for every day over the full period of observations are made based on interpolation of the concentrations that are predicted at the grid points. A further step in the calculations available in the latest version of the model, WRTDS-K (WRTDS -Kalman), is to make corrections to the predictions to ensure that they match observations exactly. The calculations were performed in the R package EGRET (Exploration and Graphics for RivEr Trends). This method relies on having a flow measurement (or prediction) for each day of the concentration observation period.

An advantage of the WRTDS method over other rating-based methods is that the time trend term does not need to fit a pre-defined functional form (except locally) (for example, it could be non-monotonic) and the relationship between concentration and flow or season does not need to be fixed over time. With the Kalman extension to the method, the predicted concentrations match the measured ones exactly. The model is highly parameterised, at the risk of over-fitting (so, for example, local relationships between flow and concentration may be over-fitted and lead to biases). A limitation of the WRTDS method is that it does not enable predictions outside the period of water quality observations, and it only provides predictions for periods where both concentrations and flow are available.

The WRTDS method was applied to water quality sites where there is also a flow record; if there were sites upstream, the upstream sites were not analysed (only the lower-most site was analysed, because it is closer to the coast and incorporates the load from upstream). The sites are listed in Table 2-1. For the Waihou at Te Aroha site, records from WRC and NIWA were spliced to form a combined record (using WRC data from July 2017). For all of these sites, there was nearby flow record of the same name. For the NIWA sites (HM5 and HM6, and AK2) and Auckland Council sites, TN concentrations were available directly because total concentrations are analysed via digestion. For WRC sites, TN was estimated from TKN plus Nitrate-Nitrite N. There were no censored data in the dataset, and there was no need to remove outliers. The data from Wairoa before 2009 were not used, because the values were suspect.

Table 2-1: Sites where WRTDS was applied. Calculated TN loads are mean annual values for the period 2010-2019.

SiteName	Region	nzsegment	SiteID	Start year	Calculated TN load (tonnes/year)
Lucas @ Gills Road	Auckland	2035811	7830	2009	4.28
Mahurangi @ Warkworth Water Treatment Plant	Auckland	2032082	6804	2009	25.02
Opanuku Stream @ Candia Road Bridge	Auckland	2038572	7904	2009	6.02
Otara @ Kennel Hill	Auckland	2040035	8205	2009	15.25
Oteha River @ Days Bridge	Auckland	2035880	7811	2009	6.57
Rangitopuni at Walkers NIWA	Auckland	2035896	AK2	1989	49.51
Vaughan Stream @ Lower Weir	Auckland	2035301	7506	2009	0.83
Wairoa River at Tourist Rd	Auckland	2041541	8516	2009	93.01
West Hoe @ Halls	Auckland	2033942	7206	2009	0.06
Kauaeranga River at Smiths Cableway/Recorder	Waikato	3044978	234_11	1993	39.75
Ohinemuri River at Karangahake Gorge NIWA	Waikato	3051925	HM6	1989	370.10
Piako River at Paeroa-Tahuna Rd Br	Waikato	3054261	749_15	1989	893.00
Tapu River at Tapu-Coroglen Rd	Waikato	3040973	954_5	1993	6.26
Waihou River at Te Aroha Combined	Waikato	3055227	HM5_1122_34	1989	1653.84
Waitoa River at Mellon Rd Recorder	Waikato	3054693	1249_18	1988	546.32

2.5.2 Rating curve methods

WRTDS only provides predictions at monitoring sites and at times when both concentrations and flow observations are available, whereas predictions are required for all terminal segments of the drainage network (segments where the network meets the coast) and for future conditions.

To enable predictions at other sites and locations, a rating-curve method was used. The method first fits rating curves at sites where flow and concentrations are measured, and then applies that rating curve to other sites or times, scaling the predictions to match the mean annual load as predicted from the CLUES catchment model (which is described in Section 2.5.4).

The rating curve followed the following form:

$$\ln(C) = a + b\,t + s(lnQ) + p(f)$$

where C is the concentration, t is the time in years (with a chosen reference year of 1990), s is a bicubic piecewise function of flow, p is a smooth periodic function with knots at 0.25, 0.5 and 0.75, and f is the fraction of the year (to represent seasonal variations). This equation was fitted using the mgcv package in R (general additive model). Bias correction factors were applied, one for flows less than the median and one for flows larger than the median.

Each terminal segment was assigned to a ‘donor’ site, based on spatial proximity and similarity of land use.

The rating curve from a donor site was applied to a terminal site using the following steps:

1. The flow time series at the terminal site was divided by the median flow at the terminal site and multiplied by the median flow at the donor site to determine flow time-series at the donor site.

2. The resulting flows were applied to the rating curve from the donor site to derive a time-series of concentrations and flux at the donor site, and a load at the donor site (not necessarily the actual load, but a hypothetical load based on the scaled flow time series from the terminal site).

3. The flux time series was scaled by a factor to give the target mean annual flux at the terminal site. The factor was the CLUES-based load at the donor site divided by the load from step 2 above.

4. Concentrations at the terminal site were determined from the scaled flux and the flows at the terminal site.

For three terminal segments (Waihou, Piako and Lucas Streams), there were two upstream donor sites each (associated with tributaries). To deal with this, at step 3, the fluxes from the two donor sites were added.

In general, when the rating curve was applied, the time in the trend term $s(t)$ was set at 2019. For historical predictions, it was not considered appropriate to apply the time trend term from the donor site because factors driving the trend at the donor site might not apply to the terminal site. An exception was if there were donor sites upstream of the terminal segment (which applied to 10 terminal segments), when including the time trend is justified based on observations at the donor site. For prediction into the future, the trend term was always based on setting the time in the trend term to 2019.

2.5.3 Combination of WRTDS and rating methods for historical time series

For historical flows, WRTDS predictions were available for locations upstream of 10 terminal segments, and those predictions were used in preference to the rating-based predictions at times when WRTDS predictions were available. The sites where WRTDS predictions were available are not at the terminal segments, so a correction was made as follows: a) Flows from WRTDS were scaled based on the ratio of mean annual flows (where the ratio is the flow at the terminal site divided by the flow at the donor site, and the flows are from Woods et al. (2006)); and b) flux values were scaled based on the ratio of loads from CLUES (terminal load divided by the donor load).

2.5.4 CLUES mean annual load model

The CLUES model (Elliott et al. 2016a; Semadeni-Davies et al. 2020) was used to predict mean annual loads of TN for each river segment in the REC drainage network. The standard version as available in December 2020 was used, except that point sources were updated for the Hauraki/Coromandel area to address errors in the standard CLUES model, based on values in Vant (2016).

Comparison between predictions in the CLUES model and loads from WRTDS over 2010-2019 showed significant bias in some cases, generally an over-prediction by CLUES (Table 2-2). It would be desirable to recalibrate CLUES to achieve a closer match to WRTDS loads in future work.

As an interim approach, correction factors were applied to the CLUES predictions to match WRTDS when using the rating curve method for generating time series, for sites downstream of WRTDS sites. The correction factors are listed in Table 2-3.

Table 2-2: Comparison between WRTDS and CLUES loads.

SiteName	WRTDS Load (t/year)	CLUES load (t/year)
Lucas @ Gills Road	4.28	3.43
Mahurangi @ Warkworth Water Treatment Plant	25.02	40.25
Opanuku Stream @ Candia Road Bridge	6.02	6.85
Otara @ Kennel Hill	15.25	12.16
Oteha River @ Days Bridge	6.57	6.96
Rangitopuni at Walkers NIWA	49.51	64.71
Vaughan Stream @ Lower Weir	0.83	1.18
Wairoa River at Tourist Rd	93.01	92.68
West Hoe @ Halls	0.06	0.99
Kauaeranga River at Smiths Cableway/Recorder	39.75	53.99
Ohinemuri River at Karangahake Gorge NIWA	370.10	512.42
Piako River at Paeroa-Tahuna Rd Br	893.00	856.06
Tapu River at Tapu-Coroglen Rd	6.26	8.86
Waihou River at Te Aroha Combined	1653.84	2070.82
Waitoa River at Mellon Rd Recorder	546.32	909.45
Sum	3705	4637

Table 2-3: Factors for CLUES. Raw CLUES values are multiplied by the factor to get the adjusted load estimate. This ensures that the adjusted load matched the WRTDS load at the monitoring sites.

River Name	Correction factor
Mahurangi	0.622
Vaughan	0.700
Lucas	1.044
Rangitopuni	0.765
Otara	1.254
Wairoa	1.004
Tapu	0.706
Kauaeranga	0.736
Waihou	0.783
Piako	0.815

2.5.5 SWAT dynamic catchment model

SWAT is a dynamic catchment model that has been applied worldwide across a wide range of catchment scales and conditions for both hydrologic and environment issues, as in reviews by Gassman et al. (2007; 2010), Douglas-Mankin et al. (2010), and Tuppad et al. (2011). To simulate a catchment, SWAT divides a catchment into multiple sub-basins, which are then subdivided into hydrological response units (HRUs), each of which has a unique combination of land use, soil characteristic, and slope. All processes modelled in SWAT are lumped at the HRU level.

Flow simulation

SWAT is typically executed using a daily time step. Simulated hydrological processes include surface runoff estimated using the Soil Conservation Service curve number method (USDA-NRCS 2004), percolation through soil layers, lateral subsurface flow, subsurface tile drainage, groundwater flow to streams from shallow aquifers, evapotranspiration, snowmelt, transmission losses from streams, water storage, and losses from ponds and reservoirs (Arnold et al. 1998). Lateral subsurface flow, or interflow, is a streamflow contribution which originates below the soil surface, but above the zone where soils are saturated with water. SWAT partitions groundwater into two aquifer systems: a shallow, unconfined aquifer which contributes return flow to streams within the catchment, and a deep confined aquifer that contributes return flow to streams outside the catchment.

Nitrogen processes

Nitrogen processes and transport are modelled by SWAT in the soil profile, in the shallow aquifer, and in the river reaches. Nitrogen processes simulated in the soil include plant uptake, mineralization, residue decomposition, immobilization, nitrification, ammonia volatilization, and denitrification. Animal grazing is not represented explicitly, but rather through manure application. Ammonium is assumed to be adsorbed onto soil particles and is not considered in nutrient transport.

Nitrate, which is very susceptible to leaching, can be lost through surface runoff, lateral flow, tile drainage and can percolate out of the soil profile and enter the shallow aquifer. Nitrate in the shallow aquifer may also be lost due to uptake by the presence of bacteria, by chemical transformation driven by change in redox potential of the aquifer, and by other processes. These processes are lumped together to represent the loss of nitrate in the aquifer by the nitrate half-life parameter. Processes that may be applied in river reaches include uptake by algae, mineralization, nitrification and settling, but were not considered in this study because of the dominance of upland processes and the time limitation of this project.

Phosphorus processes

Similar to nitrogen, phosphorus processes and transport are modelled in the soil profile, in shallow aquifer and in the river reaches. Soil phosphorus processes include plant use, mineralization and residue decomposition. Soluble phosphorus and organic P may be removed from soil via surface runoff. Phosphorus transport in the shallow aquifer is estimated based on a defined soluble phosphorus concentration and the estimated groundwater flow. Processes in the river reaches include uptake by algae, mineralization, settling and diffusion, but were not considered in this study.

2.5.6 SWAT model development for the Toenepi catchment

In this project, we used the SWAT model set up for the Toenepi catchment, a sub catchment in the Hauraki catchment, to run three scenarios: (i) Baseline 1, (ii) Baseline 2, and (iii) Climate Change scenarios.

The difference between baseline 1 and baseline 2 shows the difference in model predictions between using climate data derived from VCSN, and climate data derived from the climate model, for baseline condition. The difference between baseline 2 and climate change scenarios informs the change of flow and nutrient loadings under the impact of climate change.

The SWAT model was previously setup for the Toenepi catchment (Hoang 2019). However, this setup is simplified to use only one subbasin for the whole catchment. In the current project, we set up SWAT model for the Toenepi catchment using the predefined REC streams and sub-catchments. The shapefiles of REC streams and sub-catchment were modified to the format of SWAT input shapefiles. The SWAT model for Toenepi catchment was successfully setup using predefined REC shapefiles, in contrast to earlier modelling which used coarser subcatchments defined by topography within SWAT pre-processing software. The catchment was divided into 43 sub-catchments (Figure 2-5). The same soil and land use maps were used to further divide sub catchments into 293 HRUs. The method used to estimate nutrient inputs to the SWAT model was described previously by Hoang (2019).

The model was calibrated at the catchment outlet for both flow and water quality. Following the change of the SWAT model setup from the simplified setup done in Hoang (2019), it was necessary to adjust calibrated parameter values for flow and water quality slightly. The SWAT model simulated streamflow very well at both daily and monthly time step (Figure 2-6). The model also provides good prediction for nutrient loading, with TN and TP results shown in Figure 2-7. Further discussion of the original SWAT model for Toenepi is provided in Hoang (2019).

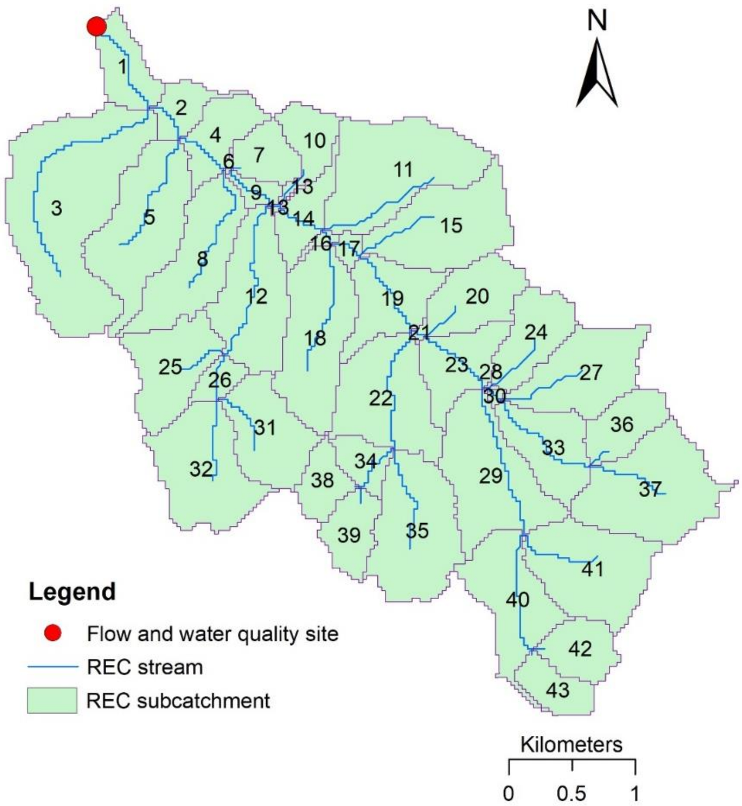


Figure 2-5: Subcatchments in the Toenepi catchment.

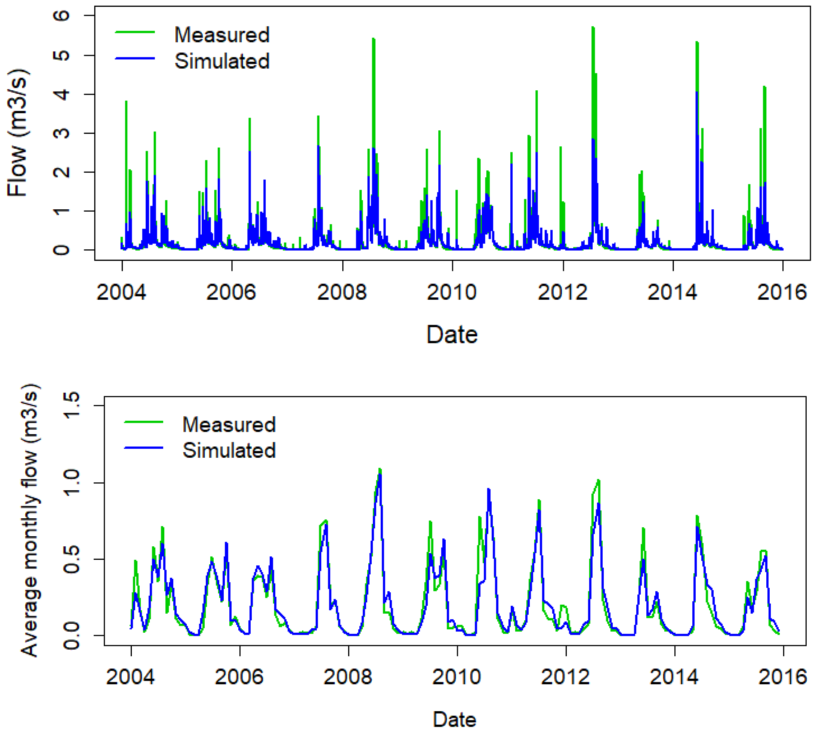
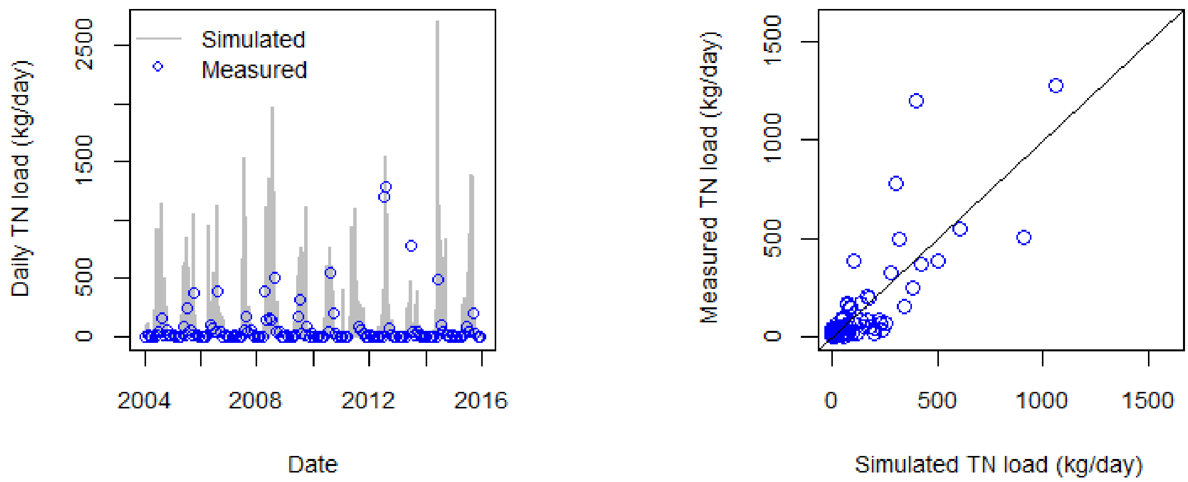


Figure 2-6: Time series of simulated streamflow versus measurements at daily and monthly time steps in the period 2004-2015.

Total N



Total P

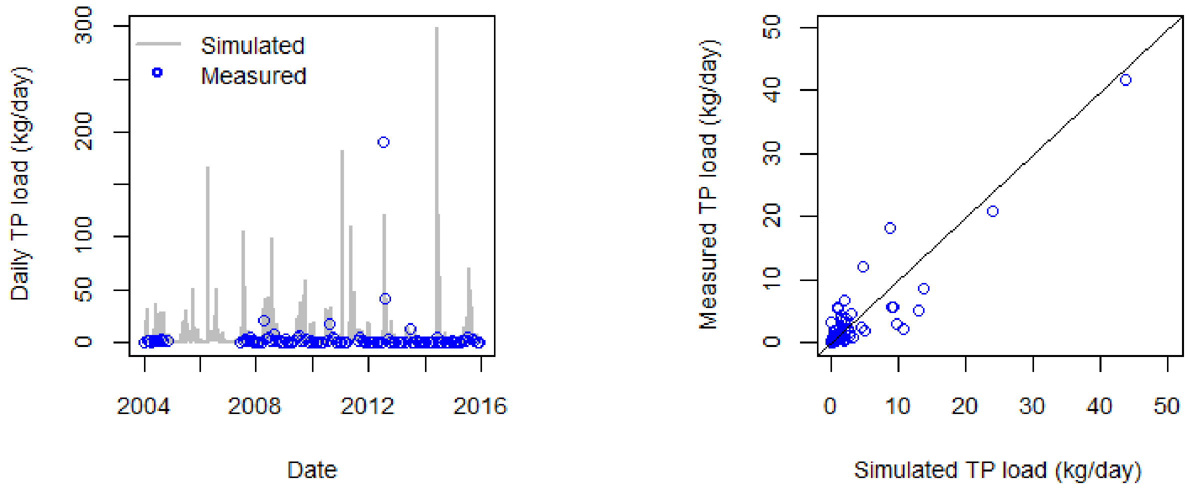


Figure 2-7: Comparison of SWAT predicted TN and TP loads versus measurement in the period 2004-2015 at the outlet of Toenepi catchment.

2.5.7 Constituents other than nitrogen

The coastal model required inputs of water quality constituents other than nitrogen. Additional required water quality variables include dissolved organic carbon (DOC) and bicarbonate ion (HCO_3^-, with simplified notation of HCO3). These were obtained from WRC and AC monitoring records for monitoring stations. The concentrations at terminal segments were taken from 'donor' sites, the same as used for rating curves. Two sites, Ohinemuri at Karangahake and Waihou at Te Aroha, did not have DOC measurements, so to get a complete dataset, the median value from other sites was used. The Auckland sites had very few HCO3 measurements, so HCO3 was estimated from alkalinity using the equation: HCO3= 1.2 Alkalinity, which was determined from other sites; this estimate is sound because alkalinity is likely to be present in bicarbonate form in the observed pH range. The resulting mean concentrations are given in Appendix B, with a summary plot in Figure 2-8.

Some interesting observations are the modest concentration of DOC (mean 3.7 mg/L) compared with inorganic carbon (mean 8.8 mg/L C based on the bicarbonate concentration). Coarse particulate carbon was not measured and may contribute to C flux to the coast, which could be addressed in future work. Dissolved oxygen concentrations were essentially saturated, but we know from other observations that dissolved oxygen concentrations in macrophyte-choked small streams are low, and the concentrations of dissolved oxygen in the lower Piako River are periodically low (Franklin and Smith 2014; Graham et al. 2017). The observed dissolved oxygen concentrations reflect the times at which DO measurements are made (during the day) and the location of the sites (in larger streams considerably upstream of their mouths). These times of measurements are unlikely to adequately represent the full range of dissolved oxygen concentrations over the diurnal cycle.

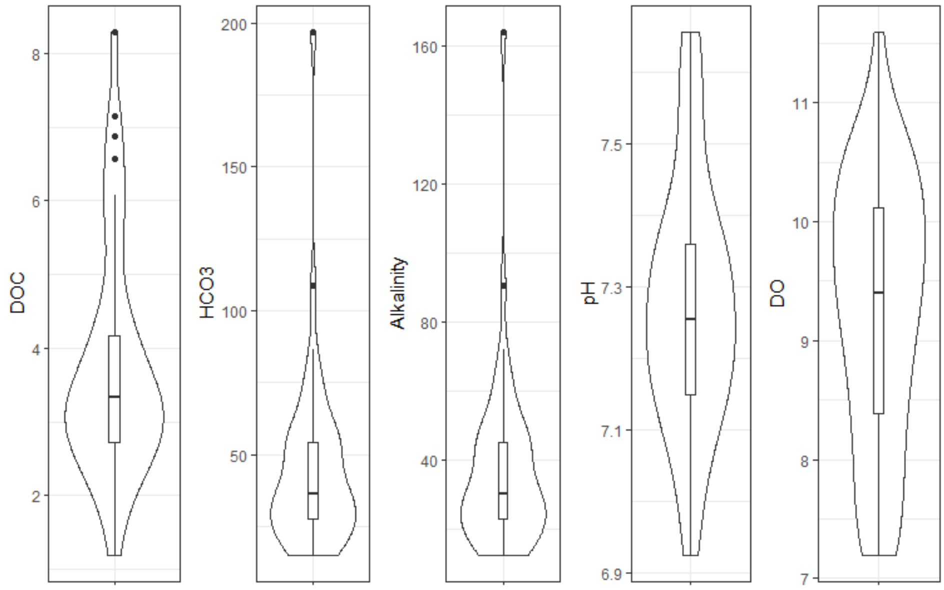


Figure 2-8: Summary plot of concentrations of constituents other than nitrogen. The distribution of mean values across sites is shown in a violin plot (probability density function) with a box plot (central horizontal lines at median, hinges at the quartiles, upper whisker to the largest data value less than 1.5 * IQR above the upper hinge where IQR is the inter-quartile range, the lower whisker is the lowest data greater than less than 1.5 * IQR below the lower hinge, and dots are data beyond the whiskers). Concentrations are mg/L except for pH (units), and Alkalinity is as mg $CaCO_3$/L.

2.5.8 Coastal sewage outfall

The Rosedale WWTP (wastewater treatment plant) discharges treated wastewater directly to the ocean via an outfall. This was added to the coastal model as a separate source. The TN load was determined from monthly monitoring records of TN concentrations and flow provided by Watercare. The mean annual flux from 2016 to 2020 was used, to avoid unusually high flows that were recorded in 2014. The resulting mean annual load was 173 t/year. This is about 2.5% of the total mean annual TN load from the catchment to the Gulf. There were no other outfalls to consider.

2.5.9 Load reduction scenario

A '**Load Reduction'** scenario was developed based on work conducted for MfE (Ministry for the Environment 2020b), following methodology similar to that used by Elliott et al. (2020). The following limits were applied:

- a concentration limit of 1 mg/L DIN (dissolved inorganic nitrogen), related to proposed ecological limits,
- a nitrate median toxicity bottom-line limit of 2.4 mg/L N from the National Policy Statement for Freshwater Management (NPS-FM, New Zealand Government 2020), and
- a TN concentration corresponding to bottom-line periphyton biomass using the 10% spatial exceedance concentrations from NPS-FM guidance (Ministry for the Environment 2020a).

These limits were applied to all terminal segments and water quality monitoring stations. For periphyton, limits were only applied if a sediment texture class <3 from the FENZ database existed.

The periphyton limit was not applied if fine sediment was present. If there were multiple limits for a location, the most restrictive limit was used.

Concentrations were used where monitored sites existed, and from empirical national models for terminal segments. The analysis (Elliott et al. (2020) provided a required load reduction (if any), for each terminal segment, which takes into account requirements upstream of the terminal segment. These reduction factors were applied to the concentration time-series for the related terminal segments.

2.5.10 Climate change scenario

The proportional load change obtained from the climate change predictions from the SWAT simulation (Section 2.5.6) were applied to all the terminal segments, to derive new estimated mean annual loads at the terminal segments. The rating-curve methods for estimating concentrations were then applied using the modified mean annual loads along with flows from the TopNet simulation to derive new time-series. This assumes that the form of the rating curves remains the same into the future (bearing in mind the flow normalisation and rescaling of fluxes that is done during application of the rating method).

The overall set of predictions related to climate change were as follows:

- **Baseline 1**. This is the 'best estimate' (most closely related to the data) of historical loadings (provided over 2009 to 2019), based on measured flows and WRTD-K interpolation of concentrations where available, and rating curves methods using flow-time-series from TopNet using the VCSN climate surfaces as described in Section 2.5.3.
- **Baseline 2.** This is for the same historical period as Baseline 1 but uses only the rating curve methods and flows from applying the downscaled climate model to TopNet. This serves as a reference for judging the effects of climate change.
- **Future Climate.** This scenario applied the load modifications from SWAT and used the rating curve methods and flows from applying the future downscaled climate predictions to TopNet.

In all cases, concentrations of constituents other than nitrogen were fixed at the historical concentrations described in Section 2.5.7.

The Future Climate scenario was mainly for illustration of the process and makes broad assumptions such as the applicability of the load change derived from SWAT for a dairy catchment to all catchments, and only a single emissions scenario and downscaled climate model was used.

2.5.11 Provision of results to the coastal model

Time series of daily concentrations and flows for each terminal segment were provided to ROMS model as a NetCDF file for each scenario.

2.6 ROMS coastal biogeochemical model

2.6.1 Physical model

The ocean physical state in the Hauraki Gulf was simulated using the Regional Ocean Modelling System (ROMS). ROMS solves equations to predict water movement, temperature, salinity, and sea-level height (Shchepetkin and McWilliams 2003, 2005).

ROMS has been designed for coastal ocean applications with terrain-following coordinates used in the vertical direction to maximize resolution in the coastal area.

The model grid has a 750 m horizontal resolution and covers the Hauraki Gulf and surrounding coastal waters (Figure 3-10). Atmospheric fluxes were sourced from NCEP (Kalnay et al. 1996), lateral coastal boundaries were sourced from HYCOM (http://www.hycom.org) and tides were imposed using NIWA's tidal model (Walters et al. 2001).

2.6.2 Biogeochemical model

Biogeochemical components of the oceanic system were modelled using the Fennel model for nitrogen cycling in the Middle Atlantic Bight (Fennel et al. 2006). The Fennel model has 2 dissolved inorganic nitrogen, 1 phytoplankton, 1 zooplankton and 2 detrital prognostic variables. It has a simple parameterisation of the exchange of nitrogen at the seafloor where nitrogen settles to the seabed and ammonium emerges (instantaneously) from the seabed. The Fennel model also calculates the chlorophyll stored in phytoplankton, which allows for an easier comparison with observations.

Lateral boundary conditions were obtained from a climatology model internal to NIWA (PISCES). PISCES has more prognostic variables than Fennel (for example, PISCES has 2 classes of phytoplankton whereas Fennel has 1). As such, some of the PISCES classes were joined to calculate the value for the corresponding class in Fennel. PISCES calculations are performed using carbon as a currency whereas Fennel uses nitrogen and a C:N ratio of 122:16 to convert between C and N.

2.6.3 Modelled scenarios

As mentioned in previous sections, there were 4 different riverine input scenarios:

1. Baseline 1
2. Baseline 2
3. Load Reduction
4. Future Climate.

For scenarios 1-3 the ROMS simulation was performed using the setup described above. For scenario 4 (future predictions), the model was set up to represent a future climate. Present day atmospheric forcing and oceanic boundary conditions from NIWA's global climate model (NZESM) were compared to future conditions (the SSP3-7.0 scenario) and the change in these variables was calculated (Behrens et al. 2020). This calculated change in oceanic variables was used as an offset, added to the ROMS modelled forcing to give a future climate forcing. For example, if the difference between NZESM present and future scenarios showed a 2 °C warming at a modelled boundary, then the scenario 4 boundary conditions would be created by the addition of 2 °C to the scenario 3 boundary condition. The offsetting method allowed us to create high resolution forcing of a future scenario.

3 Pilot modelling study key findings

The purpose of the pilot study was to demonstrate the process, and to demonstrate that we can successfully link models. Hence we do not present all the results in detail, and have limited the discussion to key points.

3.1 Flow generation

TopNet calibration in the upper Piako and for Auckland was generally successful, including the Toenepi catchment. However, we were not able to calibrate the whole Hauraki catchment successfully, due to the influence of groundwater in the lower catchment. This points to the need for coupled surface-groundwater modelling in future work. Several approaches for coupling TopNet to groundwater models are in development at NIWA, and will be trialled. There were also some issues in the upper reaches of the Piako catchment that could possibly be related to the fairly coarse (5 km) default resolution of the VCSN. In the future, the model could be run with the same parameterisation but with a version of the VCSN with a finer spatial resolution (500 m resolution). However, for climate drivers based on down-scaled GCM's, only 5 km resolution is current available, so new downscaling would be needed. Outside the catchments that have been calibrated to monitoring data, default national parameters have been used. It would be desirable to re-generalise the hydrological parameters regionally to enable transfer of recalibrated parameters to un-gauged areas.

3.2 Contaminant sources and transport

3.2.1 WRTDS for historical daily load estimation from measurements

The WRTDS method is used to estimate daily concentrations and loads over the period of historical monitoring using statistical methods. An example of WRTDS output is shown in Figure 3-1 and Figure 3-2 for the Waihou River at Te Aroha. There is an apparent increase in concentrations since 2016. From example, In Figure 3-1, for a discharge of 50 m^3/s, the concentration contours show an increase in concentration in winter from about 1.5 g/m^3 (medium blue) before 2000 to about 2.0 g/m^3 in 2019. The contours also suggest and increase in baseflow concentrations over time (at around 20 m^3/s). The mean annual concentrations in Figure 3-2 also show this trend. The increase after 2016 is discussed further in the footnote[2]. Since this is only associated with a few years of sampling, we do not consider that great weight should be given to the apparent uptick. A contrasting example is the Piako River (Figure 3-3), where there were substantial concentration reductions from about 1990 to 2000, although the concentrations have levelled out since then.

A version of the EGRET package called EGRETci (of which WRTDS is part) is available[3,4,5] (Hirsch et al. 2015) to give confidence intervals for predictions including trends using bootstrapping, but we have not trialled that software yet. The method could shed light on the confidence of predictions in future work, although bootstrapping does not address all aspects of uncertainty.

[2] The solid line in Figure 3-2 is after smoothing predicted concentrations over the range of flows, thereby making some degree of flow-adjustment to the trend, so the apparent increase in concentrations is unlikely to be due to changes in flow. There also a change in laboratory analysis methods associated with the switch from NRWQN to WRC records from July 2017, so the apparent trend could potentially be due to the switch in methods. However, there were 19 samples on matching dates in the overlapping analysis period of records (from 2015 to 2017) which had similar concentrations (mean within 3%), so the apparent trend may not be attributable to the different analysis methods. Overall we do not consider that great weight should be given to the apparent increase when there were just a few years of elevated concentrations, and the WRTDS method is less reliable at the tails of the record.

[3] https://cran.r-project.org/web/packages/EGRETci/vignettes/EGRETci.html

[4] https://cran.r-project.org/web/packages/EGRETci/index.html

[5] https://usgs-r.github.io/EGRETci/articles/prediction.html

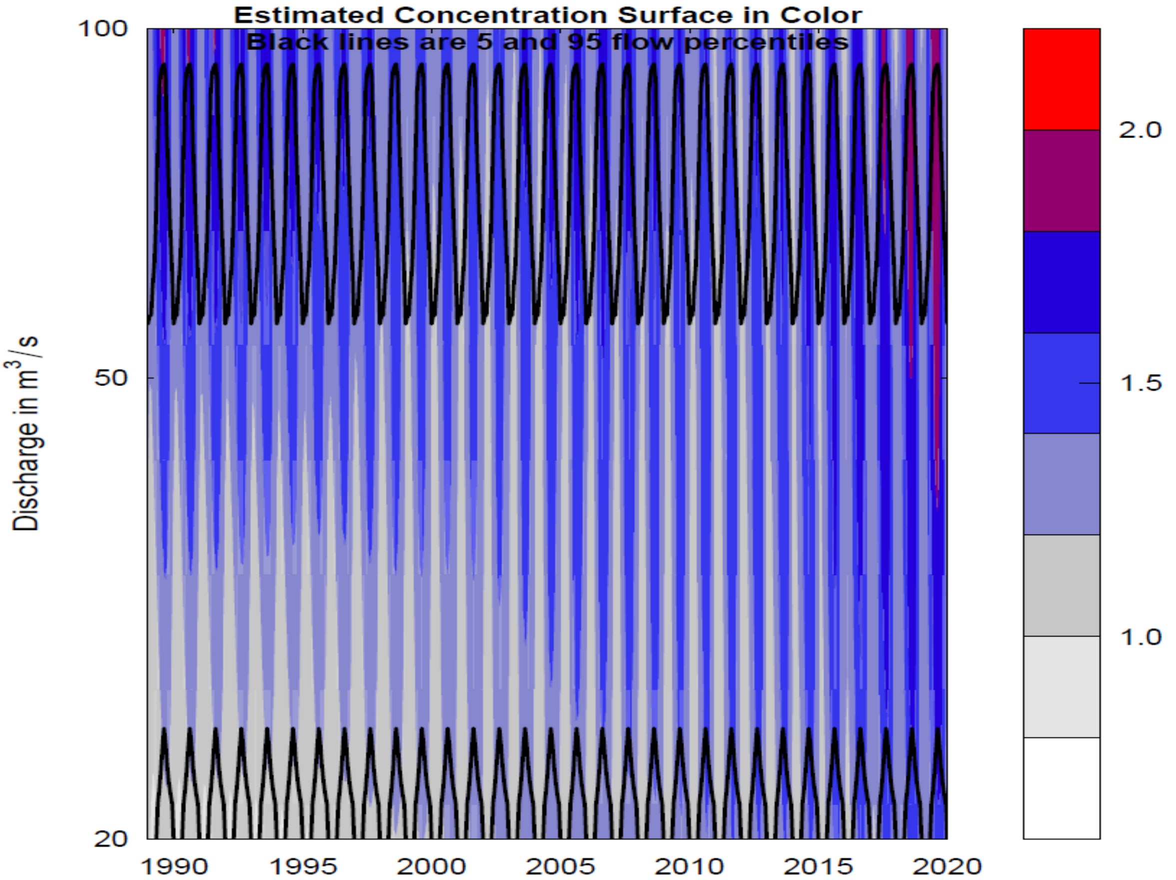


Figure 3-1: Example concentration contours for the Waihou River from WRTDS. The colours are concentrations of TN in mg/L. The coloured contours show the fitted surface of concentration as a function of discharge and time (including season). The black lines are 5 and 95th flow percentiles shown for reference purposes.

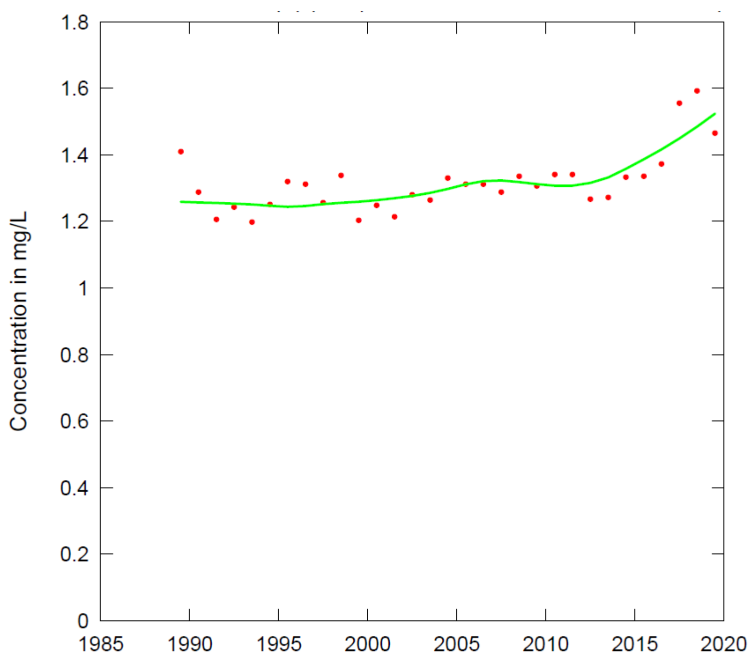


Figure 3-2: Annual concentrations of TN for the Waihou at Te Aroha site from WRTDS-K analysis. Mean annual measured concentrations (dots) and mean annual flow-normalised modelled concentrations (line).

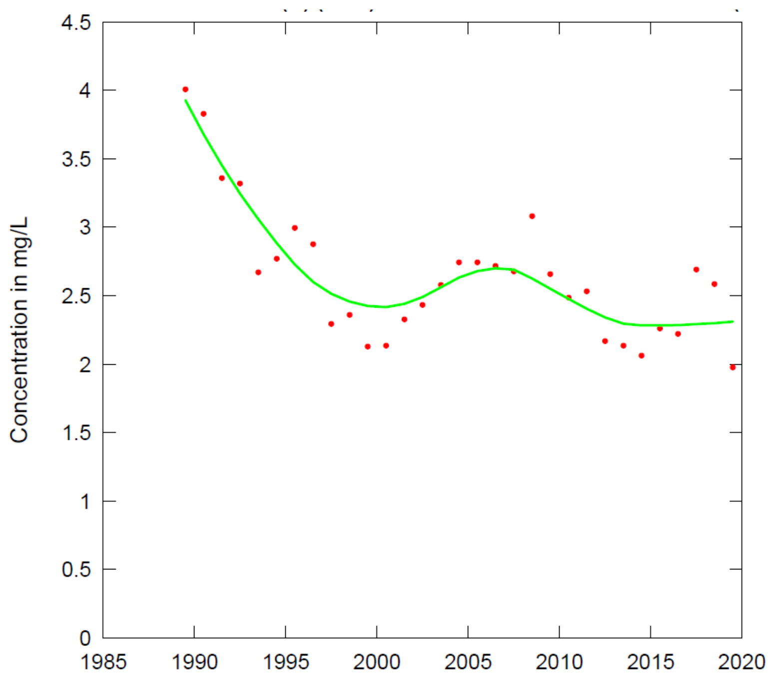


Figure 3-3: TN concentration annual time series for Piako River at Paeroa-Tahuna Rd Bridge from WRTDS-K analysis. Mean annual measured concentrations (dots) and mean annual flow-normalised modelled concentrations (line).

3.2.2 CLUES predictions

Comparison between predictions from the CLUES model and loads from WRTDS showed significant bias in some cases, generally an over-prediction (Table 2-2). The WRTDS values are the better estimate, because they are based on the measured flow and concentration records (the WRTDS are akin to a 'measured' load).

The underlying reason for the bias in CLUES predictions is unclear and could be due to source estimates being too high, or attenuation being underestimated. The bias is not consistent between catchments or land uses, and there is no obvious cause for the discrepancy based on the comparison. There is anoxic groundwater in the lower Hauraki catchment (see Elliott et al. (2018)), which may result in greater losses on nitrogen than estimated from standard CLUES parameters, but on the other hand the agreement for the Piako catchment is acceptable. It would be desirable to recalibrate CLUES to achieve a closer match to WRTDS loads in future work, and possibly to extend experimental models to incorporate groundwater explicitly into CLUES (Elliott et al. 2018). As an interim approach, correction factors were applied to the CLUES predictions to match WRTDS when using the rating curve method for generating time series, for sites downstream of WRTDS sites, as discussed in Section 2.5.4. The correction factors are listed in Table 2-3.

The total nitrogen load to the coast from all the catchment area, after bias corrections were applied, was 6885 t/year (7058 including the Rosedale WWTP). Averaged over the catchment, the total excluding the WWTP amounts to a yield of 11.8 kg/ha/year. The proportion of total load (including the WWTP) is shown by river in Figure 3-4 and tabulated in Appendix C. 73% of the total load comes from the Waihou and Piako catchments. Nearly 80% of the load comes from the top four sources. The source loads are mapped in Figure 3-5. While the load is dominated by a few rivers, some of the smaller load inputs are still associated with moderate to high yields (loads per unit area) (crosses in Figure 3-4).

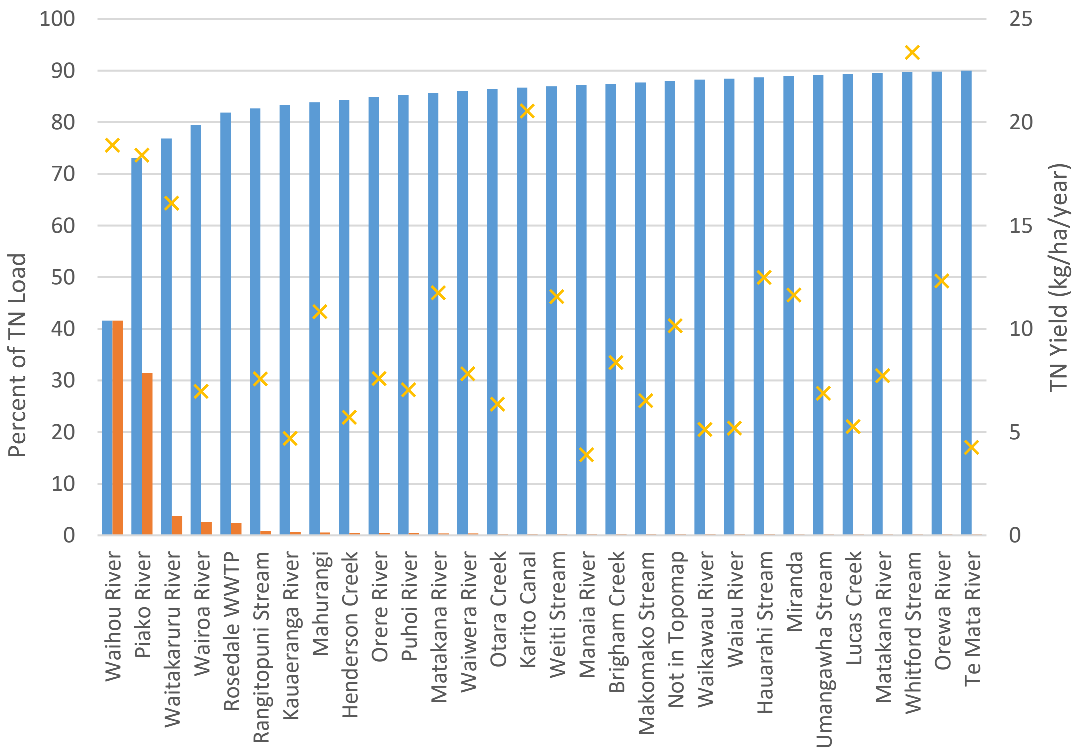


Figure 3-4: Percentage of the load to the Gulf and catchment-average TN yield from each source and the Rosedale WWTP (red columns), with largest loads on the left. Blue columns are the cumulative percentage. Only streams cumulatively yielding up to 90% of the load cumulatively are shown. The crosses are TN yields (load divided by catchment area).

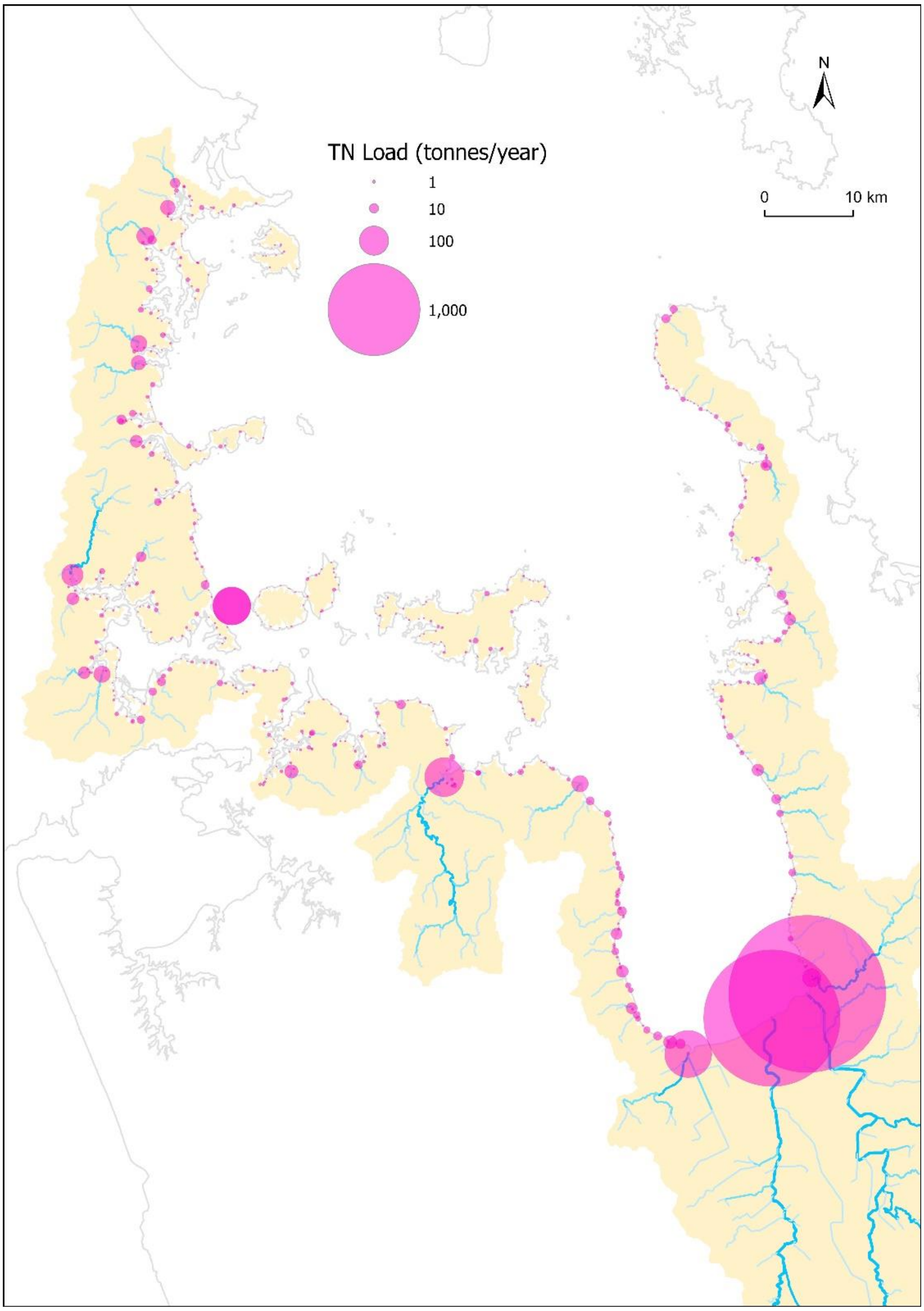


Figure 3-5: TN mean annual loads to the coast for each stream outlet. The area of the circles are proportional to the load. The Rosedale WWTP is also shown. The CLUES loads are for the Baseline 1 scenario, bias-corrected to match measured loads.

3.2.3 Load reduction scenario

To achieve the limits defined in Section 2.5.9, the modelling suggests that modest reductions in nitrogen loads were required (22% for the Waihou River and 26% for the Piako River, and about 16% for the total catchment area).

In earlier work for MfE (Elliott et al. 2016b; discussed in Elliott et al. 2020), larger reductions were required, partly because nitrogen concentrations associated with periphyton limits were lower at the time of that analysis, and partly because more locations were considered, which increased the chances of encountering a bed with coarser substrate suitable for supporting periphyton.

3.2.4 SWAT Future Climate

Comparison of climate data used in different climate scenarios

Figure 3-6 compares climate data used in different climate scenarios as input to the SWAT model: (i) Baseline 1, (ii) Baseline 2, and (iii) Future Climate. Climate data from VCSN is used in Baseline 1, while for Baseline 2, climate data derived from the HadGEM2-ES climate model for the period 2009 – 2019 was used. The climate change scenario takes the future climate data predicted by HadGEM2-ES climate model for the period 2050 – 2059. The difference in climate data is the driver of difference in model predictions shown below.

Figure 3-6 shows that within the same period, climate data of Baseline 1 and Baseline 2 is slightly different, indicating that the climate model has biases relative to the VCSN (which provides interpolated values from measured data). These biases occur because the climate model HadGEM2-ES was bias corrected for precipitation and temperature to match the seasonal climate pattern (and as a result Baseline 1 and Baseline 2 values are quite similar for rainfall and temperature), but not to match the dynamics of climate variables. The climate model was not corrected for other variables such as relative humidity, solar radiation and wind speed; as a result, the values of these variables are quite different between Baseline 1 and Baseline 2 (even though they cover the same baseline time period).

The climate model predicts that the future climate will be drier than the baseline (by comparison with the Baseline 2, which uses the same model), with lower rainfall, and higher maximum and minimum temperatures (Figure 3-6). Humidity is just slightly lower, while solar radiation increases in future. The median value of windspeed is slightly increased in future with a wider value range.

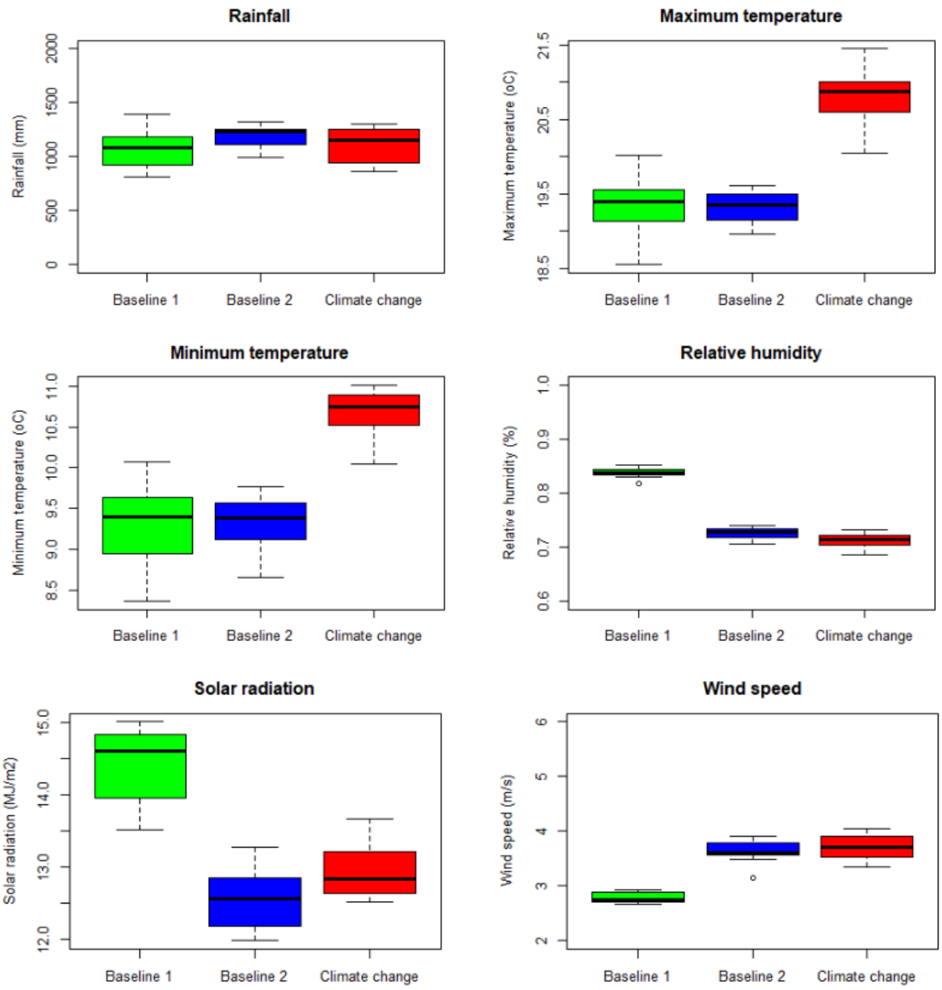


Figure 3-6: Comparison of climate data from different climate scenarios: (i) baseline 1, (ii) baseline 2 and (iii) future climate.

Comparing Baseline 1 and Baseline 2 model predictions

The SWAT model of the Toenepi catchment was run under two baseline conditions: Baseline 1 using VCSN climate data, and Baseline 2 using climate predictions from the HadGEM2-ES climate model. The previous section shows the difference in climate variables between these two baseline scenarios. The difference in climate inputs to the model, causes SWAT model predictions for the two scenarios to differ:

- seasonal patterns are quite similar,
- the magnitudes of flow, sediment and nutrient loads are also generally comparable (Figure 3-7 and Figure 3-8), and
- the values at specific times are not always the same.

Numerous storm events present in baseline 1 are missing in baseline 2 - this is because the climate model was calibrated to represent the seasonal climate pattern, but not to fit to the time series of measured climate data. It should also be noted that we only used predictions from one climate model - it is possible that another climate model would give slightly different results.

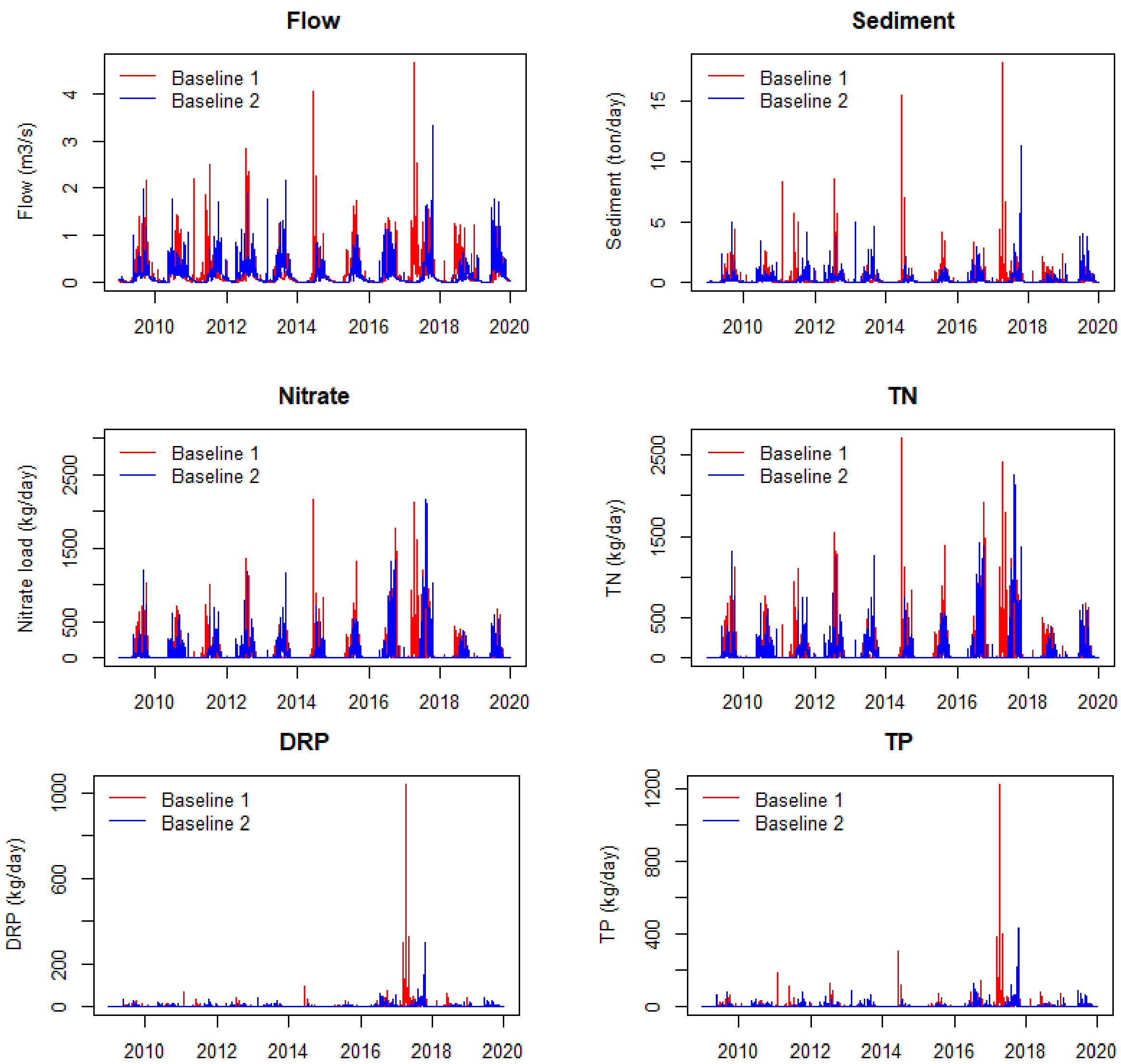


Figure 3-7: Comparison of time series of SWAT model prediction (flow, sediment and nutrient loadings) in Baseline 1 and Baseline 2 scenarios.

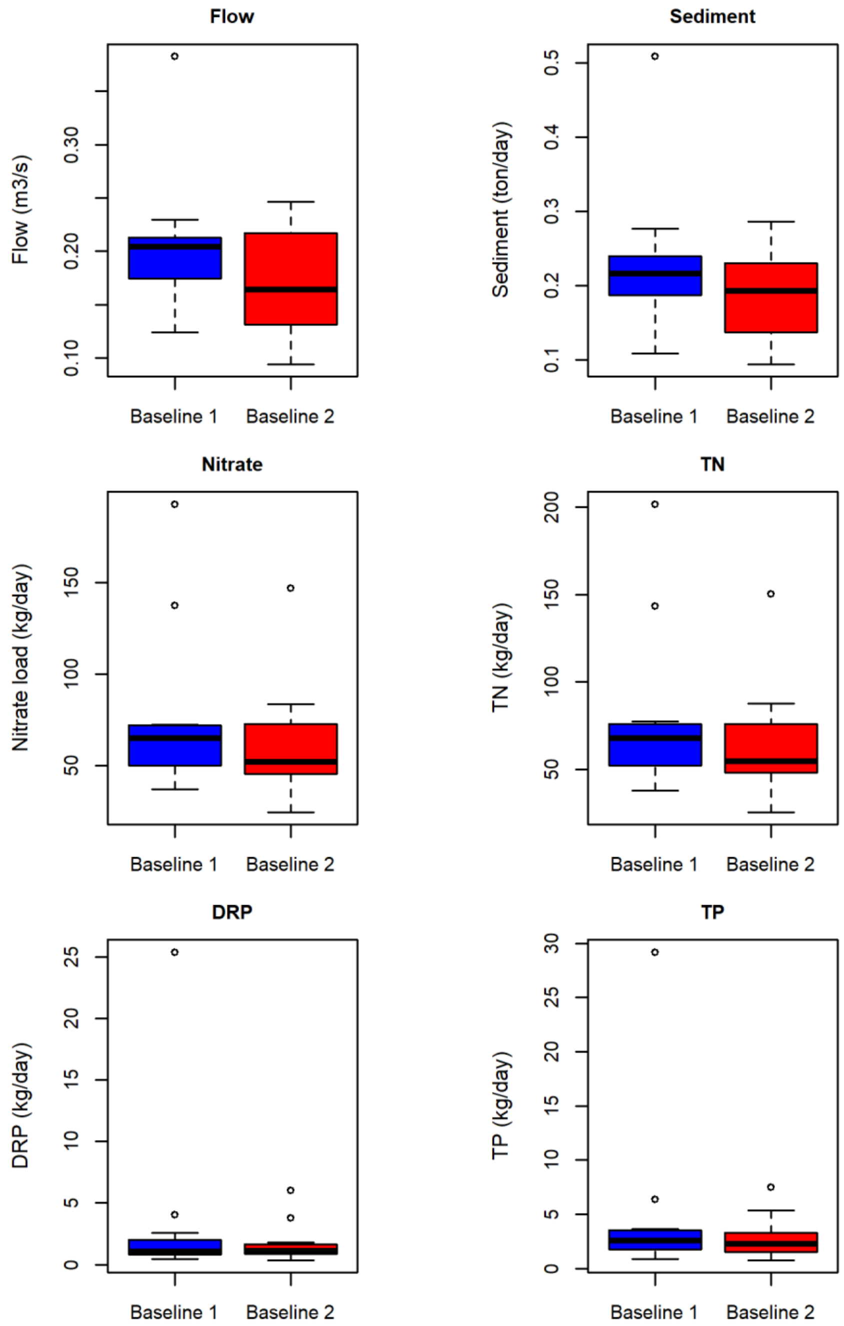


Figure 3-8: Boxplot of annual average SWAT model prediction in Baseline 1 and Baseline 2 scenarios.

Comparing Baseline 2 and Future Climate scenarios

Figure 3-9 compares model predictions under the impact of future climate relative to the baseline condition. Comparisons are made with Baseline 2 rather than Baseline 1, because Baseline 2 and the future climate scenario use the same climate model. Making comparisons using Baseline 1 instead of Baseline 2 would create the potential for predictions regarding the effect of climate change to be confounded with model biases associated with shifting from measured to modelled climate. Under the climate change scenario, flow reduces in response to decrease in precipitation and increase of maximum and minimum temperature (Figure 3-6). The flow reduction reduces loads of sediment and dissolved and total nutrient to the stream.

Table 3-1 show the average values of model load predictions in the two scenarios. The ratio of nutrient loading in the climate change scenario to baseline condition was used to estimate the change of nutrient loading from CLUES under the impact of climate change. Note that even though the nitrogen loading is predicted to decrease by about 34%, the flow is predicted to reduce by 32% under climate change, so the concentration in the river (load divided by flow) may be about the same with and without climate change; this will be explored further in future work.

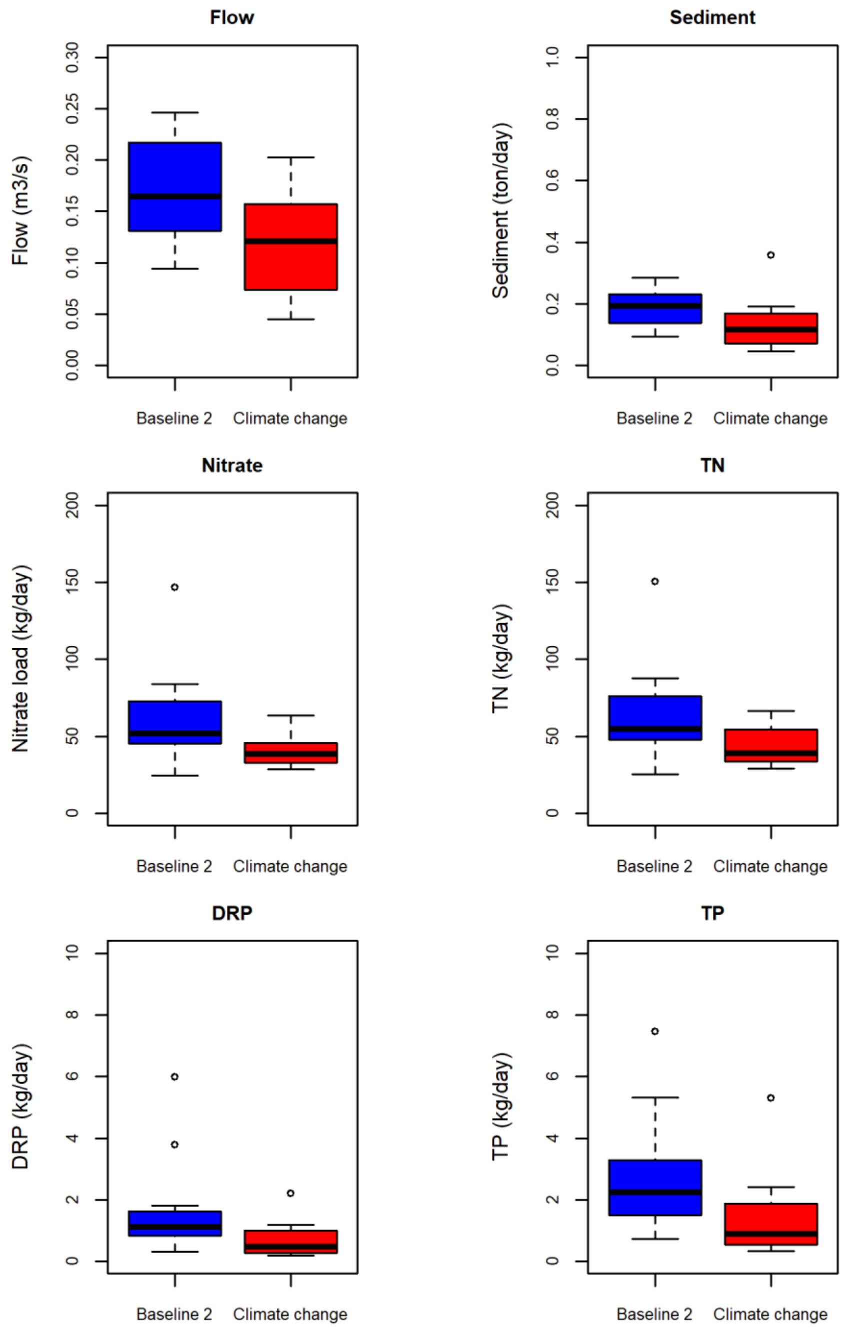


Figure 3-9: Boxplot of annual average SWAT model prediction in baseline 2 and climate change scenarios.

Table 3-1: Comparison of average values of model predictions between baseline 2 and climate change scenarios.

Variables	Baseline 2	Climate change
Flow (m^3/s)	0.170	0.118
Sediment (ton/day)	0.187	0.137
Sediment (kg/ha/year)	43.47	31.84
Nitrate load (kg/day)	62.61	41.06
Nitrate yield (kg/ha/year)	14.55	9.55
TN load (kg/day)	65.16	43.05
TN yield (kg/ha/year)	15.15	10.01
DRP load (kg/day)	1.70	0.72
DRP yield (kg/ha/year)	0.40	0.17
TP load (kg/day)	2.78	1.49
TP yield (kg/ha/year)	0.65	0.35

3.3 ROMS modelling

3.3.1 Preliminary model results

Average model outputs for surface chlorophyll and nutrients are shown in Figure 3-10 to Figure 3-15.

There are small differences between the two baseline simulations, and it is unlikely that the choice in baseline simulation would affect the model output enough to significantly alter findings from the model application. This finding is partly a result of conditioning the catchment loadings to match bias-corrected mean annual loading from CLUES, which was the same for both baseline scenarios; differences in catchment sources between the scenarios are only in the flow rates and the timing of contaminant inputs, rather than different mean annual loads.

The load reduction scenario reduces concentrations of chlorophyll and nutrients in the Hauraki Gulf region. The chlorophyll and nutrients are also reduced in the future-climate simulation. The reductions in the future scenario tend to occur near the offshore boundary and it is not clear if the change in modelled variables is being driven by the riverine inputs or the change in offshore conditions. This could be examined in future sensitivity analysis.

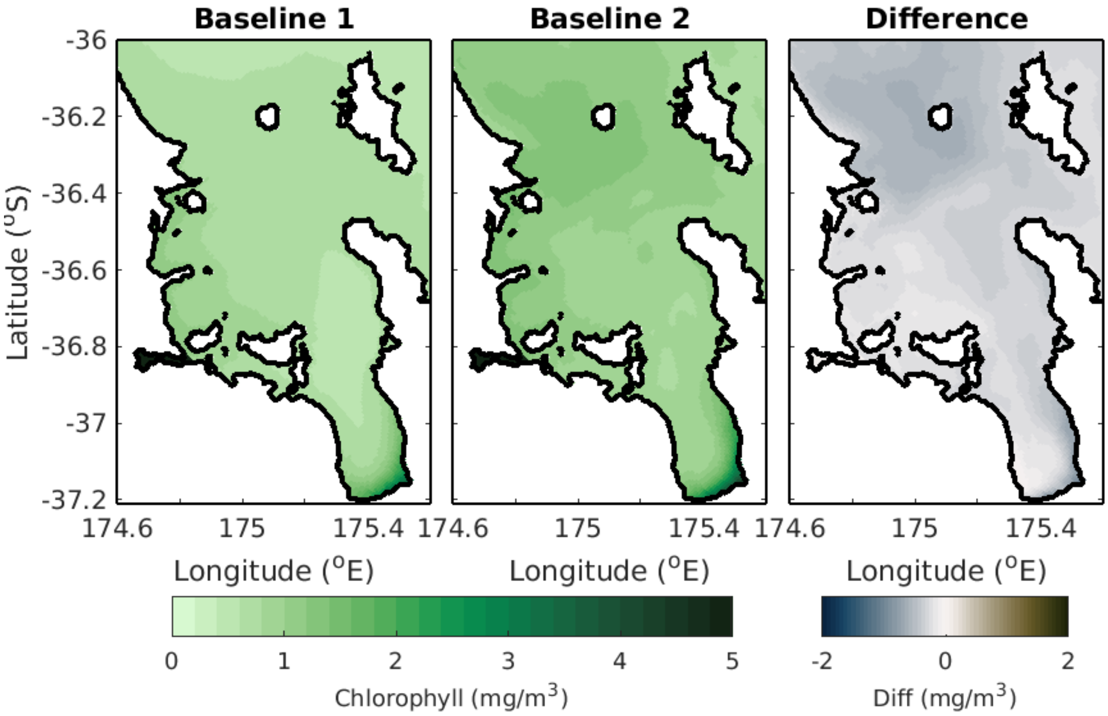


Figure 3-10: Average surface chlorophyll concentration from the ROMS coastal model for the Baseline 1 (left) and Baseline 2 (middle) scenarios. The difference between these scenarios (Baseline 1 minus Baseline) is shown on the right.

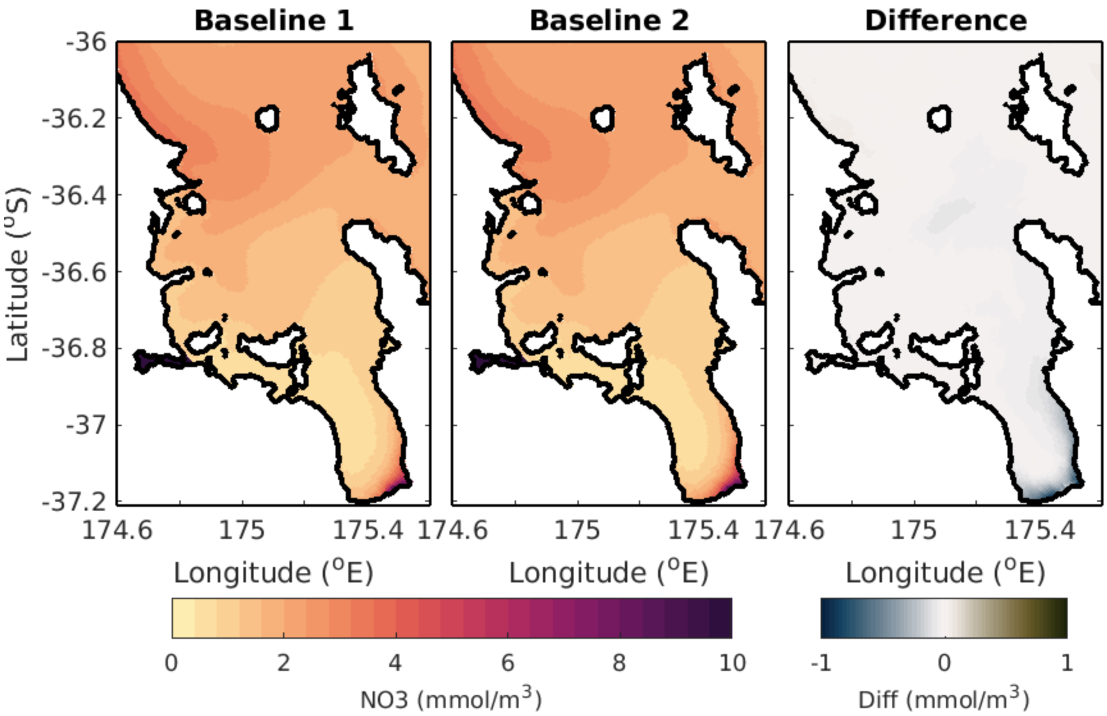


Figure 3-11: Average surface nitrate-N concentration from the ROMS coastal model for the Baseline 1 (left) and Baseline 2 (middle) scenarios. The difference between these scenarios is shown on the right.

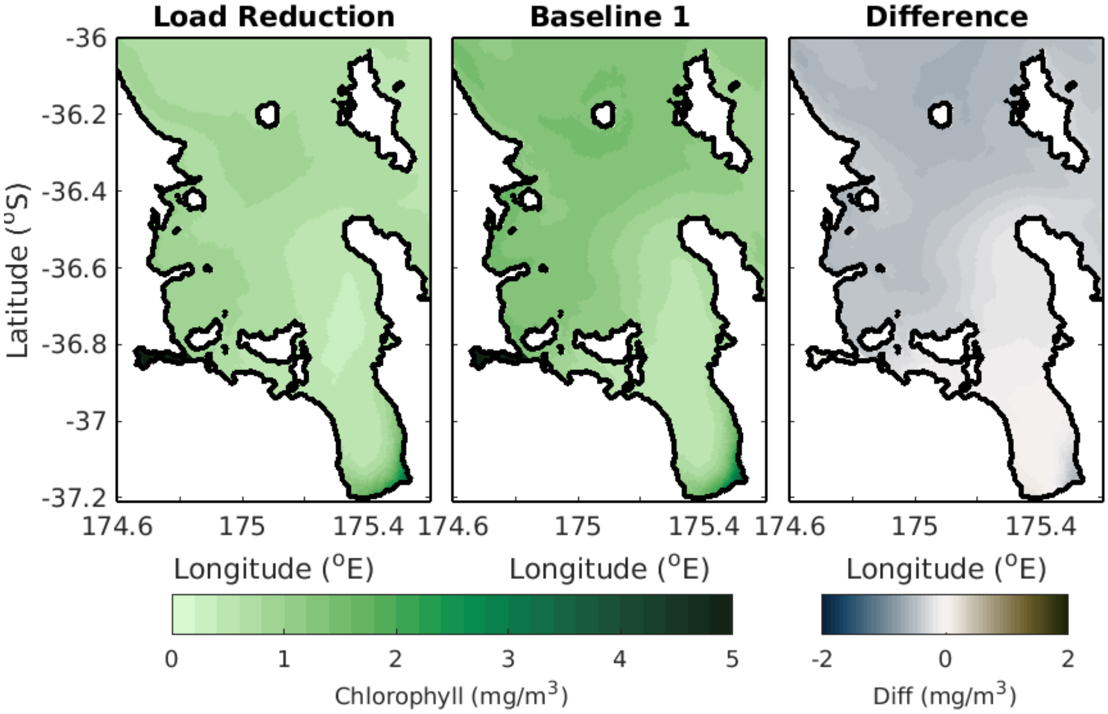


Figure 3-12: Average surface chlorophyll concentration from the ROMS coastal model for the load reduction (left) and Baseline 1 (middle) scenarios. The difference between these scenarios (Baseline 1 minus Load Reduction) is shown on the right.

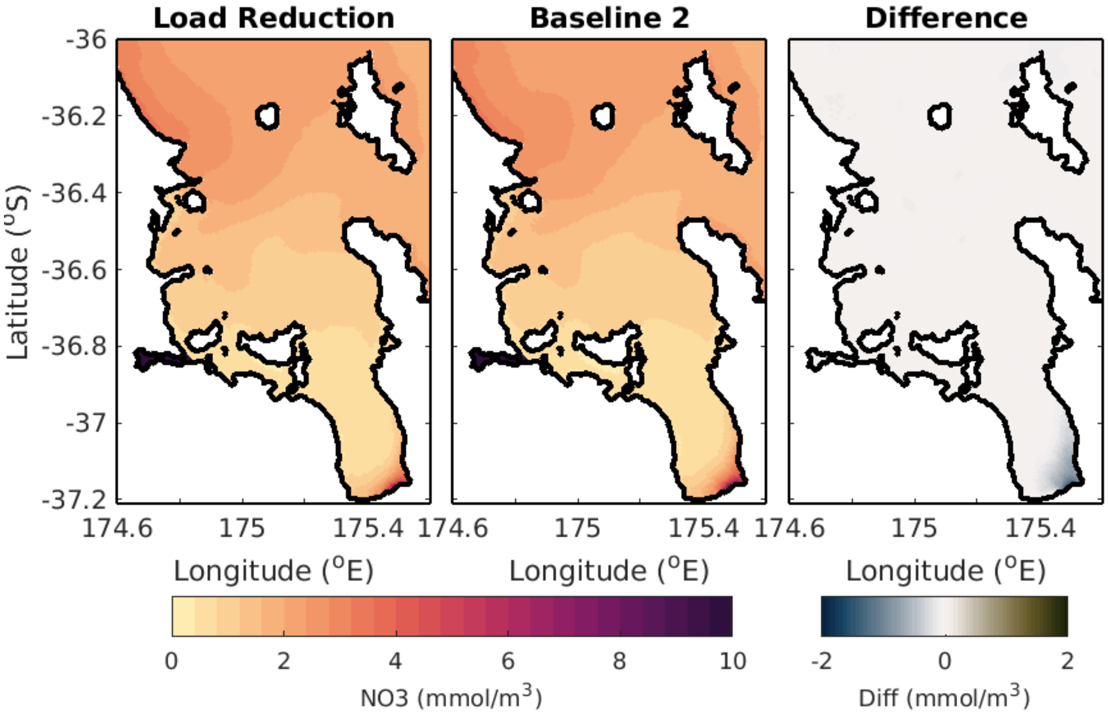


Figure 3-13: Average surface nitrate-N concentration from the ROMS coastal model for the load reduction (left) and Baseline 1 (middle) scenarios. The difference between these scenarios (Baseline 2 minus Load Reduction) is shown on the right.

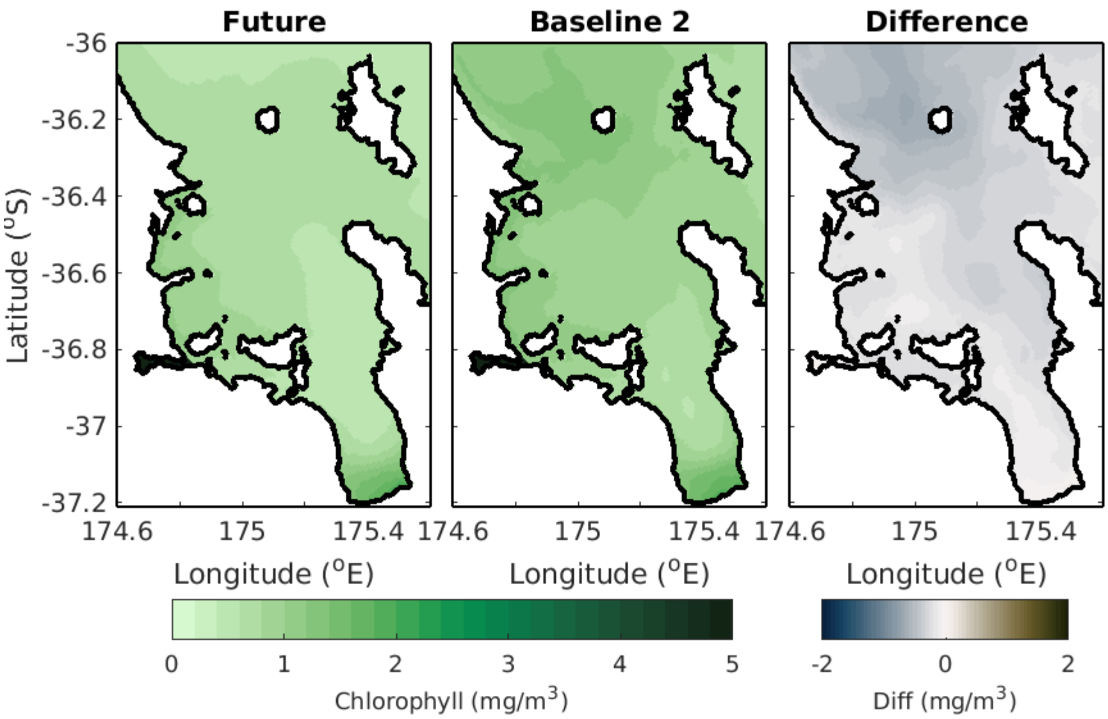


Figure 3-14: Average surface chlorophyll concentration from the ROMS coastal model for the Future (left) and Baseline 2 (middle) scenarios. The difference between these scenarios (Future minus Baseline 2) is shown on the right.

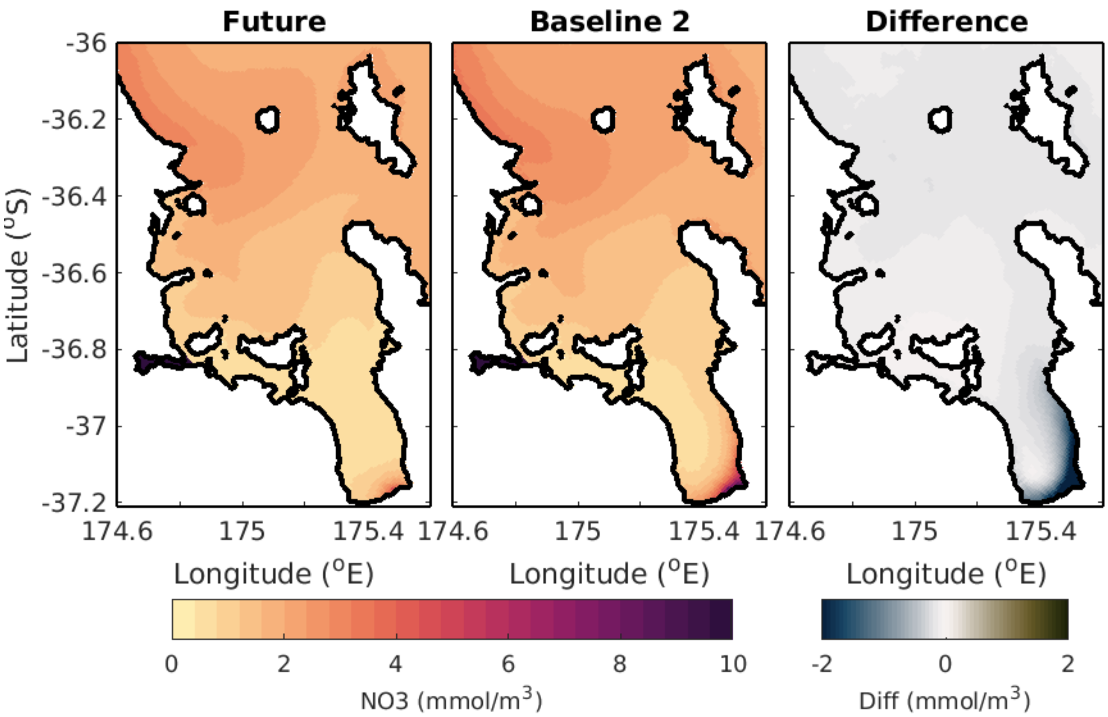


Figure 3-15: Average surface nitrate-N concentration from the ROMS coastal model for the Future (left) and Baseline 2 (middle) scenarios. The difference between these scenarios (Future minus Baseline 2) is shown on the right.

3.3.2 Model limitations and future work

The aim of this project is to develop a "proof of concept" modelling system that couples land, river and oceanic models. To date, we have demonstrated that ROMS can be coupled with daily predictions of inflows from all tributaries around the Gulf, and the model can be run over a decade period to predict nutrient concentrations and biomass in the Gulf.

However, before the model can be used for management decision-making, which is the aim of the modelling, more work on coupling the inflows to an underlying ROMS model is required. In particular, the positioning of the rivers and the model grid needs refining. In the present configuration, the added rivers make the model unstable and some of the riverine inputs become caught in isolated grid cells.

The forcing fields used for this ROMS model also need to be updated from NCEP to those of more recent, higher resolution atmospheric models. Similarly, there is about to be an update to the PISCES model (where the biogeochemical variables are sourced), and the biological boundary conditions used there should be updated as well. The marine boundary conditions used for the physics came from HYCOM. For times beyond 2018, HYCOM forecasts are needed and they use different drivers compared with hindcasts. More assessment needs to be done to determine if shifting from hindcast to forecast induces jumps or biases in the modelled outputs.

The model/data comparison needs to be updated to take account of changes to the model inputs. For example, the model was calibrated using a set of riverine inputs (generated by DairyNZ in a past project) which are different from the set of riverine inputs made in the current project. The DairyNZ study did not consider inputs from the Auckland region, were based on older data, and used a simpler regression model for calculating loads.

Additionally, climate change predictions are new for the Hauraki ROMS model and more work needs to be done to assess whether the methods used are the most suitable, and to refine the methods if necessary. For example, spatial downscaling methods were used for oceanic boundary and climate forcing for the ROM model, and their suitability of those methods for the Hauraki region needs to be confirmed through comparing the forcing with coarser-scale predictions from other models.

Finally, the exchange of nutrients between the sediments and water column is very simplistic in ROMS and a more complicated parameterisation of these fluxes should be considered to better represent this system. Hence, for future work we will investigate improvements to the representation of sediment-water exchanges.

For future work, we will consider a shift to D-Flow and D-Water Quality, once those models have been developed under separate funding (see Section 5.2.5).

3.4 Model integration and approach to scenarios

Model coupling between catchment and coast, and between the hydrologic and contaminant models, proved to be straightforward.

There were some conceptual difficulties shifting from models driven by climate and freshwater observations, to models driven by future climate and independent freshwater models. This is because shifting between observations and models can introduce bias in predictions, such that evaluation of differences between model scenarios could potentially be influenced by those biases rather than by catchment- or climate conditions. We accommodated this to some degree by bias-correcting CLUES predictions to match observations. In terms of the climate predictions, we also used a baseline scenario that was driven by modelled climate rather than observations, to serve as a basis for comparison with future climate. That approach allows a consistent climate model to be used for the future and baseline scenarios.

The approach used to predict the effects of climate change on contaminant loadings was to apply changes in mean annual loading derived from SWAT to the CLUES predictions. Currently this was based on use of the results from a single dairy-dominated sub catchment, which was acceptable for demonstrating proof of concept for the scaling approach. Although this approach could be applied to more land uses and soils combinations, it would be more appropriate to use SWAT itself over the entire catchment for baseline and future-climate predictions.

Only a single emissions scenario and downscaled GCM was used, which was acceptable for a proof of concept. In the future, for thorough assessment of climate change effects, more attention should be given to ensemble and even stochastic models, as discussed in the future work plan (section 5.7). A further aspect related to climate change is that predictions for the 'current' conditions are based on forecast rather than actual emissions scenarios, potentially introducing some bias.

4 Strategy development precursors

4.1 Workshop

A workshop was held in May 2021 with 21 people from Waikato Regional Council (WRC), Auckland Council (AC), and NIWA to:

- Provide updates on progress on NIWA modelling and the AC catchment model tool (FWMT).
- Obtain summaries of status and prospects for Hauraki modelling and supporting data collection from each institution.
- Discuss modelling needs and priorities.
- Discuss supporting data — initiatives, needs and opportunities.

Workshop minutes are provided in Appendix A, and key points are summarised below.

4.1.1 Summary of status

AC have completed the first phase of development of a dynamic Freshwater Management Tool (FWMT), which is intended to be used for limit setting and design of mitigation measures. It provides estimates of flow and contaminant runoff over the period 2012-2017. The work is being reviewed externally. Work is underway to add a mitigation optimisation tool, which aims to provide optimum configurations of mitigation measures to meet water quality targets. Upcoming work will look at linking the FWMT to receiving environment models (e.g., lakes), ecological models and coastal models, and driving the model with high-resolution climate predictions. The coastal component will focus on nearshore and small-estuarine impacts rather than the wider Gulf.

Gaps include requirement for more highly temporally resolved monitoring in streams, and ecological linkages.

NIWA has developed pilot catchment-marine biogeochemical models with applications to scenarios, as discussed elsewhere in this report.

NIWA has also developed marine hydrodynamic, wave, and sediment transport models based on Delft3D-FM and Telemac, with applications to the Waitemata Harbour and the Tamaki Estuary. Models have also been established for the Gulf (with funding from aquaculture programmes), but they are at a preliminary stage of development.

NIWA is continuing to collect water quality data from its two buoys, and there is also the potential to conduct novel monitoring involving use of an autonomous glider (or other high resolution spatial measurements) and event-based sampling.

NIWA is continuing development of the New Zealand Water Model (NZWaM), a platform with potential to link a wide range of environmental data into a modular modelling system. The physical domain of NZWaM extends from the top of the atmosphere to rivers, lakes, aquifers and estuaries. In addition to providing potential to include water quality modelling, NZWaM is able to provide estimates of hydrological data in ungauged catchments, which may assist with regional policy development. In parallel, NIWA is applying the SWAT model in several studies; some of this work will simplify set-up and use of SWAT across New Zealand. A related area of interest involves coupling SWAT and MODFLOW, a widely-used hydrogeology model.

This coupling will allow better representation of groundwater in catchments where surface-groundwater interactions are important.

In 2020, WRC commenced an enlarged programme of monitoring, including 10 sites sampled monthly (mainly in the inner Gulf) including profiles, and 2 telemetered buoys. It was agreed that discussions should be held between NIWA and the WRC to identify complementarities between the sampling programmes.

Monthly sampling is also now conducted at the Wairau and Piako mouths (since August 2020), and sonde deployments are expected in the future.

4.1.2 Model and data needs

The workshop identified that there are common model classes applicable across domains. The workshop confirmed that there is a need for underpinning hydrologic and hydrodynamic models and biogeochemical models (including sediment and nutrients), although specific models were not identified. There are also extended needs such as modelling higher trophic levels and other contaminants, but the advice from the Principal Scientists was to focus on biochemistry initially. Temporally and spatially resolved observations of flows, salinity, and biogeochemical state are critical to support calibration and validation of spatially distributed dynamic modelling. We have good data from the buoys, but there is a need to harmonise the NIWA and WRC efforts. Measurement of benthic exchange processes is a key gap, and rate processes (e.g., respiration and growth) need to be measured to complement state measurements to achieve more reliable models.

4.1.3 Prospects

The NIWA Chief Scientists for Coasts and Oceans and Freshwater and Estuaries confirmed their medium/long-term support to measurements and integrated modelling in the Hauraki system. This modelling was seen as a test-bed for development of methods for integrated modelling and application of models to meet resource management needs such as limit-setting. In the face of huge complexity, it was recommended to focus on a few key impacts initially, rather than attempting to address every aspect of the system.

Auckland Council staff were supportive of the work, but the priorities of the Council lie more with freshwater and nearshore/small-estuary impacts, rather than with the broader Gulf issues. An exception is that marine farming impacts on biogeochemistry (and the impacts of biochemistry on farming) and prospects for restoration of mussel beds were of political interest.

WRC now has less emphasis on catchment-coast integrated planning and associated science programmes than had been envisaged recently. Nevertheless, establishing marine assimilative capacity remained an important policy need, and freshwater quality is an important policy area. WRC have established new monitoring programmes in the coastal area, and there was little room to expand or modify that effort to meet particular model development requirements.

4.2 Iwi liaison

The project was raised by Niketi Toataua (NIWA Pou Ārahi) with the Iwi subgroup of the Hauraki Gulf Forum. This informed Iwi leaders of the project and created an initial point upon which deeper levels of engagement may be established. A further opportunity to raise the project with relevant parties will come at the August meeting of the Forum, where NIWA has been invited to present material to the open session of a meeting of the Governing Body.

From the map of the affected catchment, it was determined that there are many hapū in the catchment, making direct interaction with each hapū difficult. Therefore, a strategy of dealing with iwi-level organisations or collectives was adopted.

Existing Regional Council and District Council contacts were approached to determine whether there are existing points of contact with the iwi that would serve as a suitable starting point. This process is ongoing, although initial indications are that interacting with the Forum would serve as a suitable starting point.

5 Proposed strategy

5.1 Prioritised modelling aims and key model components to develop

The initial modelling workshops in 2020 identified a multitude of management questions and models relevant to the stream, lower river, and gulf, with complex abiotic and biotic interactions.

From the most recent workshop in May 2021, it was clear that there was a need for limit setting in relation to a core set of biochemical attributes including sediment, nutrients, and primary eutrophication responses (phytoplankton, dissolved oxygen), with a need for sound underpinning representation of hydraulics. While there was also interest in higher trophic levels, the Chief Scientists recommended focussing on a few key impacts initially, rather than attempting to address every aspect of the system.

While sediment was acknowledged as an important driver of ecological responses, the available marine models at Gulf scale are not sufficiently developed to enable full coupling of sediment and eutrophication models at this stage.

The proposed work programme has been developed to address the following questions:

- What will be the degree, frequency and duration of algal proliferations, and dissolved oxygen depletion in the Gulf, under different levels of nutrient loading and under climate change?
- How will these responses affect benthic ecological health?
- What reduction in catchment nutrient loads are needed to achieve given eutrophication attributes in the Gulf?
- How much will it cost to introduce mitigation measures to reduce these loadings (at an indicative level)?
- How do these reductions compare with what is indicated from nitrogen-based attributes for stream and river ecosystem health variables, including periphyton?
- If load reductions for protection of the Gulf are achieved, will they also prevent de-oxygenation episodes in the lower Waihou and Piako Rivers?

5.2 Proposed model system

The basic model architecture is based on a set of linked and potentially exchangeable models, to enable limit setting, as shown schematically in Figure 5-1. The key components include:

- catchment nutrient and flow sources,
- mitigation costing,
- river transport and effects on river ecosystems,
- gulf transport and biochemical state in the water column and in the sea bed, and
- gulf ecological impacts.

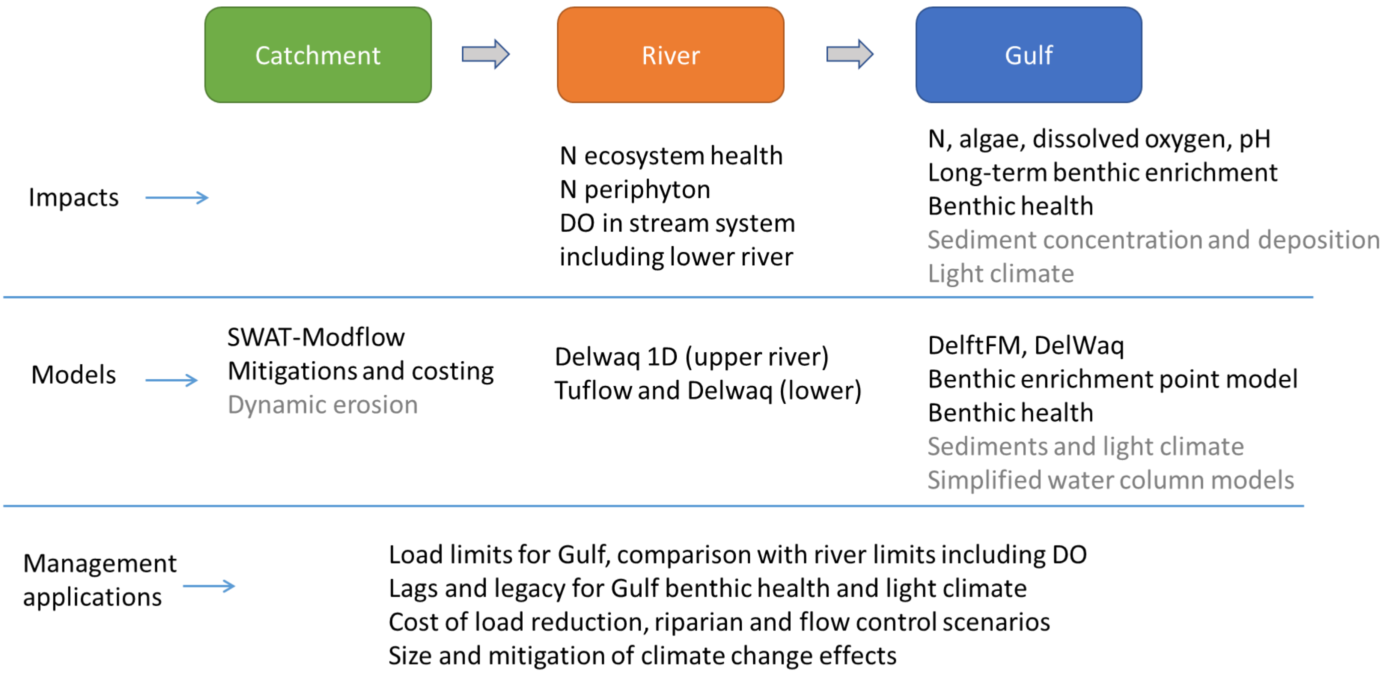


Figure 5-1: Proposed set of models and their relationship to impacts and management applications. The light grey items will be addressed in future, potentially requiring other models.

Work to date in this project has successfully demonstrated the linking of catchment flow and contaminant generation to Gulf biochemical models. For the proposed work programme, specific sub-models are proposed, building on past work but adding critical components where necessary.

5.2.1 Catchment nutrient and flow sources

To date, this project has used empirical rating-based methods, the catchment model CLUES, and rating-based temporal disaggregation driven by flows from the TopNet model. SWAT was used to predict changes in nutrient loading from a dairy area in response to a climate change scenario. This model was suitable for the prototype.

For future work, we proposed to shift primary responsibility for flow and contaminant generation on to the catchment model SWAT. This will enable a mechanistic representation of catchment nutrient sources including land use change, coupling to dynamic contaminant input to river biogeochemical models, and representation of climate change impacts, providing consistency between flow and contaminant loading models.

While SWAT has been applied successfully in New Zealand in small agricultural and mixed catchments (in the order of 10 km^2), a key technical challenge will be to scale up the model for the full Hauraki catchment. The total catchment area is 5858 km^2, involving 12800 REC2 Strahler 1 subcatchments. This will require application to a much larger area than done previously in New Zealand. Hence the model domain will need to be split up into sub-domains, model setup will need to be automated and the models will need to be set up on a high-performance platform. Should these requirements prove to be too demanding, coarser subcatchment agglomerations may be necessary.

While Auckland Council have developed a catchment model (FWMT) for the Auckland catchment, and some of the modelling approaches are attractive (e.g., coupling to mitigation optimisation), the model has not been finalised, is not available to other parties to set up and modify, and has some limitations in terms of representing the soil-plant system. Also, TN loading from Auckland represents about 14% of the nitrogen loading to the Gulf (based on CLUES). Therefore our proposed approach is to use SWAT, although coupling with FWMT could be considered in the future.

5.2.2 Mitigation costing and effects

We propose to apply mitigation costing and effects approaches developed by Yvonne Matthews in the NIWA Mitigation Systems Programme. These will be applied to 'smart' scenarios that take cost-effectiveness and practicability into account. While some mitigation measures could be simulated directly within SWAT, others will need to be implemented as source reduction factors applied to SWAT outputs.

5.2.3 Freshwater (upper) river modelling

While SWAT can transport contaminants through a river system, it does not predict complex biochemical processes leading to de-oxygenation. Building on work in a 2020-21 SSIF project, we will couple SWAT flow and contaminant sources to DELWAQ (Deltares Water Quality model). DELWAQ is a sophisticated contaminant transport and transformation model can be applied to freshwater and marine systems. Currently, the SWAT-DELWAQ approach has been applied to the Toenepi Stream. As with the SWAT model, this extended river modelling will require automated setup along with large-scale computing, with model simplification (modelling only the mainstem) as a fall-back option.

5.2.4 Lower river modelling

To model the complex yet important de-oxygenation in the lower Waihou and Piako Rivers, it is proposed to use a 3-D version of DELWAQ. A 3-D model of the hydrodynamics in the lower river is available (implemented in the Tuflow software), and that can be coupled to DELWAQ. This accounts for salinity, stratification, tidal effects, and residual recirculation.

5.2.5 Gulf eutrophication

The ROMS model was used for work in the 2020-21 year. It was chosen over the Delft3D-FM and DELWAQ models[6] because it has already been set up for water quality calculations in the Hauraki Gulf, and it also provides a good representation of stratification dynamics, whereas Delft3D-FM was still being set up and DELWAQ implementation had not commenced.

While the ROMS has been set up, it still needs to be calibrated and tested for water quality predictions (nitrogen, algae, dissolved oxygen). Also, the empirical terms for benthic remineralisation need to be addressed further and compared with measurements. We do not consider that it would be feasible to introduce a full benthic model within the available timeframe and resources, so will use an empirical remineralisation model.

Following calibration, sensitivity analysis will be conducted to determine the sensitivity of key eutrophication attributes to modification of land and fish farm inputs, benthic sources, and climate change, to identify key management levers and to assist with identification of source load limits.

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[6] Software from Deltares.
https://www.deltares.nl/en/software/delft3d-flexible-mesh-suite/
https://oss.deltares.nl/web/delft3d/delwaq1

In the long term, the Delft3D-FM/ DELWAQ model has appeal, because it is considerably more sophisticated in its representation of biochemical processes including sediment transport and benthic processes. A DELWAQ model is being developed for the Hauraki Gulf under other funding, but currently we are unsure how well it will perform. We have therefore allowed for comparison of ROMS and Delft3D-FM/ DELWAQ (apart from desktop comparisons done to date), with a possible shift to Delft3D-FM/ DELWAQ for future modelling (or its use as a companion to ROMS), depending on the outcome of the comparison.

5.2.6 Gulf benthic enrichment

In the Gulf, representation of benthic sources of nutrients and organic matter was considered to be important. Empirical models for ROMS are available, and they could be calibrated to past and proposed measurements of benthic processes, as an approximation. However, it is also important to predict the long-term benthic nutrient enrichment, both to provide inputs to benthic health sub-models and to long-term cumulative and legacy effects relevant to limit-setting. The current detailed models for the Gulf (ROMS and potentially DELWAQ in the future) run too slowly to allow for representation of long-term accumulation (even if the model formulation caters for such processes); it is therefore proposed to develop a simplified model of long-term sediment enrichment.

5.2.7 Benthic ecological health

To complement the biochemical models in the Gulf, it is proposed to include some representation of ecological effects.

First, existing literature will be used to establish ecological thresholds for DO, nutrients, and primary production, which the models are able to predict. Comparing predicted state against these thresholds will provide a preliminary look at water quality status in relation to ecology, but will not predict the status of the ecological communities or take account of multiple stressors.

Benthic communities are an important part of the marine ecosystem, and they respond to physical and biochemical factors such as light, sediment enrichment and texture, and dissolved oxygen. Based on new field observations, it is proposed to develop Bayes Net models of benthic communities, with associated ratings of ecological quality. This will help link land inputs and biochemical processes to ecological state, thereby assisting with establishment of load limits. It is noted, however, that there are other stressors such as human bed disturbance and fishing pressure which also impact benthic communities, which could be considered in a broader ecological assessment but is beyond the scope of the proposed modelling.

5.2.8 Climate change scenarios

The work in the project to date used a single climate scenario and a single climate model from downscaled CMIP5 predictions. During the timeframe of this project, it is expected that downscaled predictions from CMIP6 (Phase 6 of the Climate Model Integrated Project), associated with the sixth cycle of IPCC assessments) will be available. They will incorporate climate impacts measured to date and will provide a more recent baseline condition than that used to date. It is proposed to use these updated predictions.

Additionally, a wider range of climate models will be run, to better gauge uncertainty of water quality and eutrophication predictions associated with emissions forecast and model formulations.

5.2.9 Future extensions

The proposed programme focusses on a key set of biophysical attributes and processes. We envisage that the following features could be delivered by adding processes in existing models or adding new model components:

- **Sediment** is an important stressor, especially for locations near major sources of sediment. This includes effects of sediment on visual clarity and light climate in the water column and for benthos, and also for smothering, food quality, and sediment texture. Work is underway in related programmes to build sediment models for part of the Gulf; previous attempts to model Gulf-wide sedimentation had limited success. It is anticipated that in future work, some of these models will have been trialled further, and will be suitable for application to the Gulf. In particular, we consider that the Deltares models (Delft3D-FM and DELWAQ) have promise. On the freshwater side, SWAT can provide predictions of sediment loading, but the ability to represent mass erosion, including bank erosion, is limited, so that extensions to SWAT are likely to be required. An alternative would be to introduce a separate dynamic catchment erosion and transport model which is being developed by Manaaki Whenua with involvement from NIWA; it is possible however that the timing of sediment loading may be incompatible with timing of flows and nutrients from SWAT. These factors can be considered when (or if) a future round of research is designed.
- **Visual clarity and light climate**. This is an important factor for primary production and biological effects. A future model could use sediment predictions from the sediment generation and transport models, in conjunction with specific representation of light transmission and clarity, to predict the influence of sediment and algae on the light climate in the Gulf. This work will potentially ingest results derived from spatial light climate models currently under development in other estuaries.
- **Microphytobenthos** component. In shallow and intertidal areas, microphytobenthos can make a large contribution to primary production, yet they are not incorporated in ROMS. In recent modelling for the Manukau Harbour, a modified microphytobenthos model has been added to DELWAQ. This could be an important improvement and could be preceded by approximate calculations of the area of suitable depths and information on production in the main part of the gulf.
- **Simplified box models for the Gulf,** providing contaminant transport and eutrophication capability. Both the ROMS model applied to date and the alternative Deltares models require long run times (typically weeks) to make predictions over a decade. This creates difficulties for rapid exploration of multiple scenarios and uncertainty, and for predicting long-term behaviour of the system (for example, long term changes in sediment composition or response to infrequent events). This is a common problem for detailed mechanistic models. In the work programme we propose to introduce a simplified model for representing long-term sediment enrichment and legacies. However, we also see the potential to simplify the water-column model to represent key parts of the system in a faster model. One approach used for Baltic Sea long-term modelling (Murray et al. 2019) was to apply a set of 1-D (in the vertical direction) models, with a set of interlinked basins, but such a representation would not be suitable for the Hauraki Gulf.

It is likely that a box-compartment model including lateral and vertical exchanges would be more appropriate. Use could also be made of source-distribution and re-distribution models as done for modelling sediment distribution and heavy metal accumulation in shallow estuaries in previous NIWA work.

- **Stochastic climate change models**. Typically, to generate a range of predictions under future climate change, an ensemble of different climate models is run. However, the models are deterministic. If large events are important, then they may not be sampled adequately within a 10-year simulation period. Ideally, a stochastic component would be introduced to obtain a better representation of large events. There is some precedent for setting up stochastic simulations, and also of modifying historical records to represent expected changes in the statistical distribution of events, as done in Climate Change Impacts and Implications MBIE programme. Such work would require close collaboration with climate modelling specialists.
- **Incorporation of remote sensing data.** There are opportunities to collect and use remotely-sensed spatial marine data to test and improve the models. For example, models could make use of low-level satellite observations of water optical characteristics, and marine glider data (as discussed in the workshop). There are no concrete plans currently to undertake such observations, but they could lead to considerable spatial and temporal detail and associated system understanding and model improvements.

5.3 Supporting data collation and collection

The proposed work programme requires the following (limited) data collection, in addition to the marine and freshwater monitoring already being undertaken or proposed by NIWA and WRC (see the workshop notes for further details of current and anticipated monitoring):

- Benthic seafloor community characteristics at 6 sites (Figure 5-2), as an adjunct to a previously-planned cruise of the Ikatere.

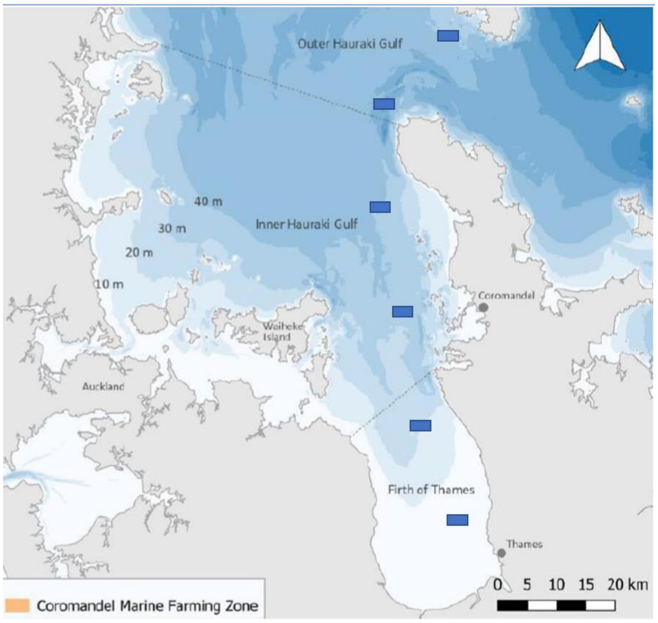

Figure 5-2: Proposed sites for benthic health assessment.

We note, however, that the following fieldwork is already planned under other funding:

- Ongoing buoy instrumentation, at 4 sites. 2 of these are funded by NIWA. We are initiating discussions with WRC to examine whether there can be some rationalisation of the sites.
- Ongoing SOE sampling of the Gulf (commenced 2020), and ongoing NIWA sampling accompanying buoy maintenance and download operations.
- Benthic flux measurements, to be undertaken by the University of Auckland and AUT, funded by WRC. This will help in modelling the benthic flux.
- Regular sampling at the lower Wairau and Piako bridges, and planned sonde deployments at these locations.

We are also discussing with WRC the possibility of adding organic carbon to their suite of analyses, at least for a 1-year period, to provide more information on terrestrial carbon exports to the coastal system.

It would be desirable to add a comprehensive field programme that includes the following components:

- benthic flux measurements across a range of sub-environments
- measurement of benthic enrichment status, including addition of isotopic measurements
- organic matter composition measurements in the water column
- deployment of marine gliders
- capture and analysis of low-level aerial imagery
- paleo-stratigraphy to analyse the history of enrichment and historical reference conditions. Previous work on sedimentation in the Hauraki Gulf (Boxberg et al. 2019) showed little evidence (from seismic analysis and cores) of recent anthropic sediment or heavy metal accumulation in the outer part of our study area (in the basin to the west of the top of Coromandel Peninsula), in contrast to thick deposits in the Coromandel Harbour and the Firth. We may be able to use those cores in collaborative work to establish the history of enrichment and historical reference conditions.

Although additional monitoring could fill important knowledge gaps, the available budget and the emphasis on modelling does not allow for such additional monitoring.

5.4 Model integration

Catchment-coast integration to date has relied on a fairly simple approach of providing daily flows and constituent concentrations to the coast at each stream outlet to the coast (from the REC2), with data exchange in NetCDF format. Also, in related projects, we have provided SWAT flow and constituent loads into the river system as simple time series files for each stream segment being modelled, at REC level. This loose coupling approach proved to be flexible and allowed for modellers in different areas to conduct their part of modelling in isolation (but in a sequential fashion). In future, we propose to use essentially the same approach, which will provide flexibility and simplicity.

More reliance will be placed on SWAT to provide both flows and contaminants, but using the same overall approach to exchanging data with the coastal component. If the lower river is introduced explicitly into the modelling chain between the upper river and coast, it could be included using the same overall approach, except that a summarisation stage would be required to represent inflows to the marine system in a simple way.

5.5 Management applications

The following applications are anticipated in the work programme:

1. Sensitivity analysis to assess key drivers of estuary eutrophication.
2. Comparison of model predictions with tentative marine limits on dissolved oxygen, nutrients, pH and primary production.
3. Comparison of model predictions with benthic community health goals at selected sites.
4. Determination of catchment nitrogen load limits to meet Gulf targets, including consideration of the impacts of climate change. Assessment of dissolved oxygen depletion risks in the lower Waihou and Piako in response to altered nutrient sources.
5. Assessment of freshwater load limits to meet freshwater objectives, and comparison of estuarine load limits to freshwater load limits to determine the most restrictive system.
6. Preliminary design and costing of catchment mitigations to achieve target loading, including application of SWAT scenarios. Note that this will not be a comprehensive assessment unless additional resources are secured.

5.6 Dissemination of models, model results, and general liaison

The model system is intended to provide a practical demonstration of the use of coupled models for integrated catchment-marine management. One way to improve the credibility of the modelling is to prepare peer-reviewed journal articles. We foresee an article on the model sensitivity work and one on the integrated assessment, although given the timeframe of the project and applications the second paper may not be published by the end of the funding period. We also propose to share the work in two local/regional science conferences.

It has been suggested by the WRC that Sandy Elliott be embedded in the WRC one day a week to help facilitate the two-way interaction between policy/limit-setting and modelling (and associated data collection) activities. This still needs to be agreed and formalised.

Considering the intended wider use of integrated models for limit-setting in New Zealand, we propose to showcase this work to Regional Councils annually through webinars or workshops. This may lead to additional applications of the approach to other regions, extension of the models to address particular issues in other regions, and identification of gaps. MfE will be included in these information exchange exercises.

We also proposed to build on the initial Iwi liaison. The depth and nature of this engagement is currently uncertain but considering that Iwi have a key role in management of natural resources generally in terms of Te Mana O Te Wai, and in the Hauraki specifically, we expect that a deeper level of engagement will evolve over time. This liaison will also take account of existing and developing Council-Iwi relationships.

NIWA has an invitation to present this programme to the Hauraki Gulf Forum in August. The presentation will initially be to inform them of our progress and intentions, but we hope that it will also lead to higher-level support of the project from the high-profile members of the Forum's Board.

5.7 Work plan and timeline

A tentative work plan is shown in Figure 5-3. The plan is spread over 3 years to enable a focus on useful products in the short term in conjunction with ongoing model development and improvement. Enactment of this work plan will depend on available resources. Note also that the data collection exercises outside the SSIF programme are not shown. It is anticipated that the timeframe of the work will ultimately extend beyond 3 years, to enable additional important and innovative model development, and incorporation of data derived from fieldwork activities such as those suggested in Section 5.2.9.

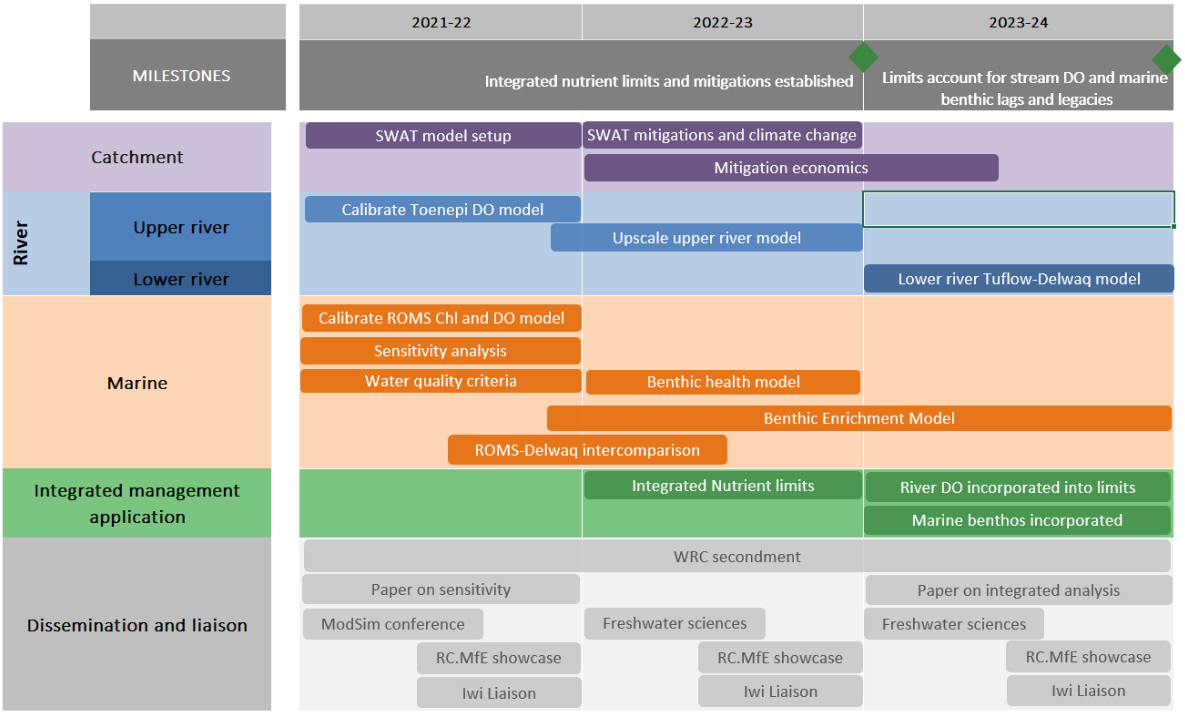

Figure 5-3: Tentative work plan.

6 Conclusions

The pilot modelling study demonstrated the feasibility of linking catchment and coastal models to predict coastal eutrophication responses over a decadal time-scale, and applying these models to assess implications of nutrient source reduction and climate change.

Application of these models revealed the need for various refinements and extensions to meet high-priority management needs. Key items are:

- Transition the catchment model to SWAT.
- Refine the ROMS coastal eutrophication model, with possible transitioning to Delft3D-FM and DELWAQ.
- Development of a model to enable better quantification of benthic state and nutrient flux, including long-term aspects.
- Add dissolved oxygen models for the streams and rivers.
- Add a marine benthic health model.
- Add a mitigation economics model.

Iwi liaison has been initiated at the 'inform' level, but it is anticipated that there will be deeper engagement in the future.

Most of the required data collection is underway or anticipated to be undertaken by Regional Councils or NIWA. An exception is a survey of benthic health to inform the development of a benthic health model.

An ambitious programme for model development has been proposed to address high-priority needs, including application in a conjunctive land-water limit-setting context and dissemination. Several opportunities to expand the scope of work beyond the proposed programme have also been identified. Interactions with Regional Councils will continue, including investigation of co-funding opportunities and application of the integrated modelling approach to other catchment-estuary systems.

7 Acknowledgements

We thank Waikato Regional Council, Auckland Council, and NIWA staff for providing data and for their contributions to the Workshop (see Appendix A for specific workshop contributors).

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Appendix A Workshop minutes

(Minutes start on the next page)

Hauraki Integrated Land-Water Modelling Workshop Notes

Sandy Elliott, 13 May 2021

20 April 2021, NIWA Hamilton

Attendees:

WRC	Mike Townsend	Thomas Wilding
	John Hadfield	Janine Kamke
AC	Tom Stephens	Coral Grant
	Theo Kpodonu	
NIWA	Sandy Elliott	John Zeldis
	Helen MacDonald	Joe O'Callaghan
	Christian Zammit	Andrew Swales
	Linh Hoang	Scott Larned
	Glen Reeve	Barb Hayden
	Niall Broekhuizen	Scott Nodder
	John Zeldis	Charine Collins

Apologies: Hannah Jones, Tuana Kuka, Nick Brown, Neale Hudson

Presentations (presenter name in parentheses):

- Introduction, scene-setting (Sandy Elliott)*
- Auckland Council FWMT catchment modelling (Tom Stephens)*
- Hauraki catchment workshop summary (John Hadfield)
- NIWA nutrient source and transport modelling and integration (Sandy Elliott, Linh Hoang)*
- NIWA coastal ROMS modelling (Helen MacDonald)*
- NIWA Hauraki Gulf and Tamaki Strait Delft3D and Telemac models (Glen Reeve)*
- NIWA Coastal monitoring (Charine Colins)*
- WRC Coastal monitoring (Janine Kamke)*
- Waikato Regional Council status and prospects overview (Michael Townsend)
- Auckland Council status and prospects overview (Coral Grant)

PowerPoint presentations (marked with *) are shown in handout form at the end of these minutes. They contain important points raised by the presenters. The full presentations have been set up on a Microsoft Teams site and a link has been sent to the participants.

John Hadfield (Hauraki catchment workshop):

- WRC held a workshop in 2020 about Hauraki catchment modelling and measurements. Mainly a show-and-tell to encourage sharing and collaboration.
- Need simple models, but complex models to benchmark them
- There is still a need to improve representation of uncertainty.
- Council planning process for Hauraki/Coromandel will probably not have full coastal-catchment integration that was originally envisaged.

Mike Townsend (WRC perspectives and prospects):

- WRC are about to enter a new LTP cycle (21/22) with limited increases in science spending.
- Coastal and marine science is a Strategic priority and there should be increased focus on estuaries with the NPS-FM, although the NPS-FM in general will keep a lot of folks busy.
- WRC haven’t adopted a programme structure in the science section that was proposed at one point.

However, there are key parts from the Hauraki 'Mountains to Sea' concept that they will be progressing' particularly around ecosystem and stressor connectivity and freshwater-saline water transitions.

- Within estuaries the WRC is data poor, especially in the low saline sections.
- Our coastal plan review is underway, which needs to identify degraded waters and link water quality with values and take into account the Regional Policy Statement which discusses *assimilative capacity* [so it would help to quantify assimilative capacity]. In short there are many areas where we need improved understanding and tools for assessing water bodies and understanding the stressors on them.
- WRC have plenty of needed work in the Firth of Thames, around aquaculture, Sea Change objectives and a need to understand sediment and nutrients loads where modelling and novel data collection could be informative.
- Currently WRC have a shovel-ready project for Manaia, which will take a catchment perspective and look to implement effective actions to make measurable improvements.
- We need knowledge that *informs stakeholders* and *supports management decision*s in a challenging and changing future. This mean models need to be designed for or at least capable of providing management-relevant information i.e. designed to answer management relevant questions.
- Currently the WRC's main research focus relevant to this project is on:
    - Structure of the Waihou and Piako rivers/estuaries
    - Nutrient and sediment dynamics – annual sediment yields.
    - NPS-FM – limit setting appropriate for coastal/estuarine systems.
    - Behaviour under events – in addition to more normal.
- There are other parts of WRC's work that may be tangentially or indirectly related to modelling efforts such as the role of mangroves and seagrass in estuarine processes, the distribution of vegetation such as *Spyridia filamentosa,* and measurement of the rates of denitrification in the Firth of Thames.

Coral Grant (AC RIMU perspectives and prospects):

- Loads to the coast relevant under the NPSFM
- Interested in the implications of aquaculture and the nutrient carrying capacity of the Firth/Gulf.
- Need to provide tools for better assessment of consents. Current models are piecemeal, not used consistently, and are not accessible. This includes models from consultants.
- More monitoring of offshore aquaculture will be needed.
- Better collaboration with WRC is needed.
- Uncertain how various modelling initiatives (MetOcean, NIWA, WETS) interlink and complement each other.
- Tools are needed to distil learnings and outputs form models for use in management, including messaging and comms.
- AC is expanding monitoring. 10 new staff approved.
- Would like data that is currently held in consents reporting to be made available in a central database, because it could help with overall monitoring knowledge. Consent holders support this.

Model identification
A breakout session with follow-up compilation and reporting was conducted.
This resulted in a list of models classified by environmental domain and type. Most of the proposed modelling centred around nutrients, oxygen, and sediment, phytoplankton and acidification, along with associated dynamics of water movement. There was little prioritisation between modelling.
There was also mention of the need to model higher ecological levels and values, and aquaculture (effects of an on water quality and biogeochemical processing).

Priorities
AC noted that effects on the smaller estuaries and embayments was seen as of a higher priority than eutrophication and acidification of the Firth.
JZ considered that biogeochemistry and seasonal dynamics are a priority question.
Mike considered sediment-nutrient interactions as a key priority to quantify.
Tom stressed the need to understand the relative role of freshwater versus marine limits. Which is more sensitive? Are there some marine locations that are more sensitive than others? This was mostly in the context of near-shore and small estuary impacts.
Coral saw the coastal fringe and estuaries as a priority (reflected AC direction). Also, there is a need to link and combine models. Also supported JZ emphasis on biogeochemistry. Some key issues are sediment, nutrients, restoration (e.g., mussel reefs).
Mike Townsend. The Firth is already highly impacted, and a unique headache (unusual processes, condition). Smaller estuaries have better ecosystem health [and perhaps more emphasis should be on them?]

Discussion of supporting data
Monitoring *processes* in subtidal/benthic environments is needed, not just state. That applies especially to benthic-pelagic coupling. There is a real gap in understanding and representation of benthic processes and exchange. For example there is a lot of primary production on the bed surface considering the large intertidal and subtidal area.
Can we harmonise the monitoring buoys that are currently deployed in the FoT? There is currently no co-ordination currently between NIWA & WRC. FoT is a low priority for AC monitoring; need to discuss further - are these in the right locations? **Action**: Set up meeting to discuss harmonisation of buoy data and field campaigns.
There are opportunities to match buoy instrumentation to remote-sensing requirements (e.g., SCENZ project, MattP, MarkG). There are precedents in other NIWA and DOC studies.
Remote-sensing, surface water and under-water sampling is needed for monitoring/model validation as well as buoys.
Spatial survey data to support modelling is possibly now provided by WRC SoE coverage in inner FoT by WRC (monthly since 2020). 10 sites, depth samples at one site, CTD profiles. However, they are designed for SoE reporting and may not be suitable for modelling (e.g., no carbon-based parameters) - need for further discussion to match modelling requirements. **Action**: Set up meeting to discuss integration and extension of WRC SOE monitoring.
Also, there were sampling campaigns in August 2020 from bridges in the Waihou and Piako. There are opportunities to fine-tune this and do more spatial sampling int eh lower Piako.

Funding prospects
AC have prioritised smaller estuaries not the Firth.
WRC have no headroom in their sampling budget.
NIWA is committed to medium/long-term funding of integrated modelling and work in the Gulf.

Comments from the Chief Scientists

Scott Larned:

- Emphasis should be on joining up models in an integrated approach to address RC issues. Joined-up modelling is an important area of science, research and development very relevant to limit-setting.
- FOT modelling project is not just about the Firth, but is more generally about *methods development* for linking models and apply them to management needs such as limit setting.
- Likes the AC approach of a clear path from model questions, to outputs to regional plan rules.

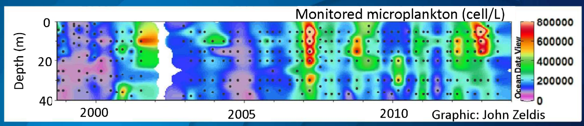
Barb Hayden:

- The system is hugely complex, but we need to focus on a few key impacts of the work to have manageable objectives and to achieve outcomes (make a difference). Need to focus on council needs.
- Agrees with Scott's points. Development of methods that can be applied elsewhere.

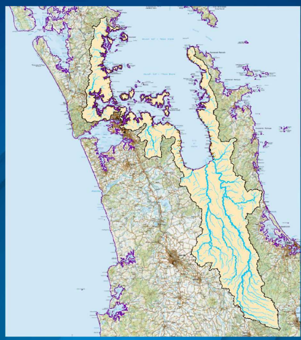
Hauraki Integrated Land-Water Modelling Workshop

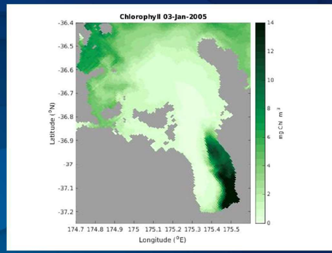
Scene-setting presentation

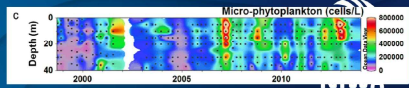
Sandy Elliott



Graphic: John Zeldis







What this is ultimately about:

Support limit-setting and land-water management by using integrated models to predict the effects of climate change and management measures on ecological, socio-economic and cultural values in the coastal zone and freshwater.

Today's workshop

Aim:
Commence planning for collaborative integrated modelling and supporting data collection.

Agenda
- Scene setting
- Presentations on progress and opportunities

Lunch
- Future modelling strategy exercise
- Supporting data exercise
- Closure/synthesis

What are the management needs (from earlier workshops)?

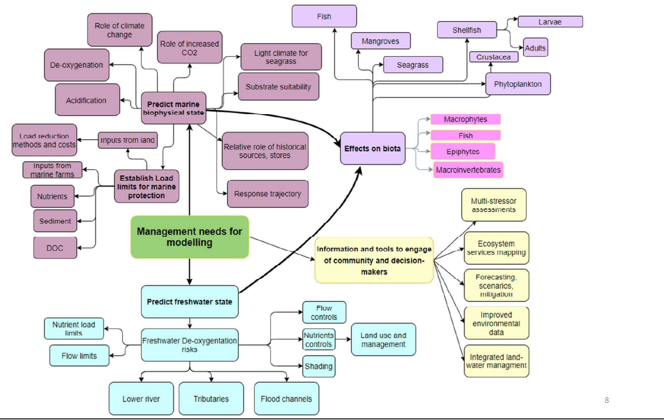
- **Determine contaminant load limits**. How much do contaminant (nutrient, sediment, carbon) inputs from land to the coast need to be reduced to protect Gulf ecology (aquaculture, larvae, mussel beds)? Catchment ↔ Coast perspective. (Plan Change 2 and current RPS Policy 7.2.4 c).
- Quantify risks for **eutrophication** in the Gulf (**blooms**, **de-oxygenation and acidification,** and **biological implications** for fish and shellfish larvae and mussel beds)
- Risks of **de-oxygenation of rivers** (lower Piako, macrophyte-dominated tributaries, backed-up flood channels), and role of flow modification, shading, nutrient controls for management.
- Risks for **sediment effects on seagrass and spawning success** (reduced light, benthic sediment quality)?
- Quantify the role of new and existing **marine farms** (finfish and mussel) in local and Gulf eutrophication?
- How could **contaminant load reductions** be achieved, and at what cost?
- What are **implications of climate change and increased CO_2** for load limits?

Management needs (2)

- **Predict recovery trajectory.** How long will it take for the marine system to recover once sources are reduced? How strong are legacy effects, sediment remobilisation and mineralisation? Will health will get worse for a time even if land inputs remain constant? How will climate change affect the trajectory? Will delays in acting prolong recovery timeframe or endpoint (hysteresis, irreversibility)?
- **Provide spatial layers for marine spatial planning** e.g. benthic sediment suitability for larval spawning
- Put **biogeochemical deterioration risks into context of other ecological pressures** (e.g. fishing). Multi-stressor view.
- Some **simple models to complement complex dynamic models** (conceptual, Bayesian Network, box), for rapid scenario assessment and communication of concepts and risks (direction and magnitude of change) to decision-makers.
- Need **tools to package and communicate** model results and understandings for decision-making.
- Spur and guide further **data collection**.

Additional science/modelling questions

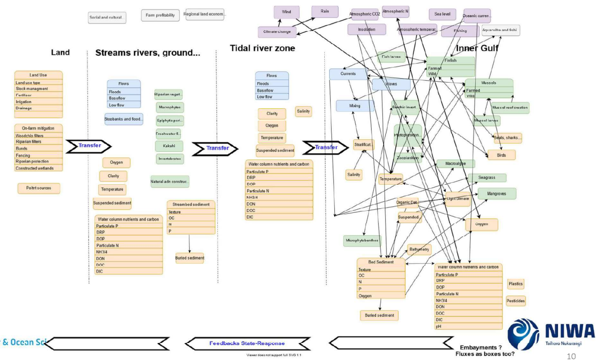
- **Role of events**. How much do events (climate, storm, marine) influence ecological health versus average (annual average, season) conditions. Sediment, mangroves, hypoxia, DOC, seagrass, toxic blooms…?
- What will be the **relative contributions of land inputs versus climate change** to acidification?
- Investigate using **new types of data to improve modelling** e.g. **new sensors** in the lower Wairoa, remote sensing (in addition to mooring and SOE monitoring)
- Are there **critical indicators of biogeochemical deterioration**. E.g. benthic process rates or state? Can identify find these?
- What is the **relative role of internal loads and sediment remobilisation versus ongoing catchment sources**?



Some simpler views

- Predict time, location, timing and degree of risks
- Identify key management levers
- Predict success of management actions and policies

Driver → Pressure → State/process → Impact → Response



Making a start: NIWA SSIF seed project, 1 year

A cross-centre cross-disciplinary modelling initiative:

1. Conduct a pilot modelling exercise to demonstrate integration of selected existing models
2. Develop a broad strategy and framework for future integrated modelling and supporting data collection

Existing NIWA models summary for selection

Catchment and freshwater
- Topnet
- CLUES
- Erosion yield estimates
- SWAT

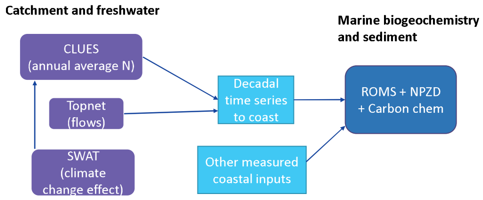
Lower river
- Telemac Waihou salinity and flow

Marine biogeochemistry and sediment
- LOICZ
- ROMS + NPZD + Carbon chemistry
- Delft3D + Sediment
- Delft-FM + DelWaq

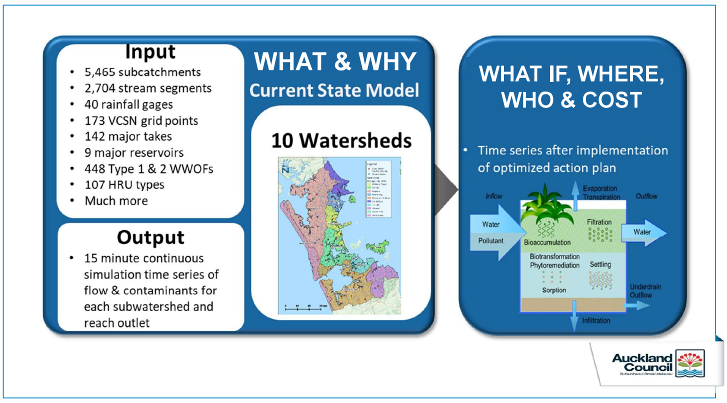
Marine impacts
- Tidal flat evolution (point model)
- Mussel larval drift
- Ecosystem services spatial planning
- Optical environment for seagrass
- Snapper BN

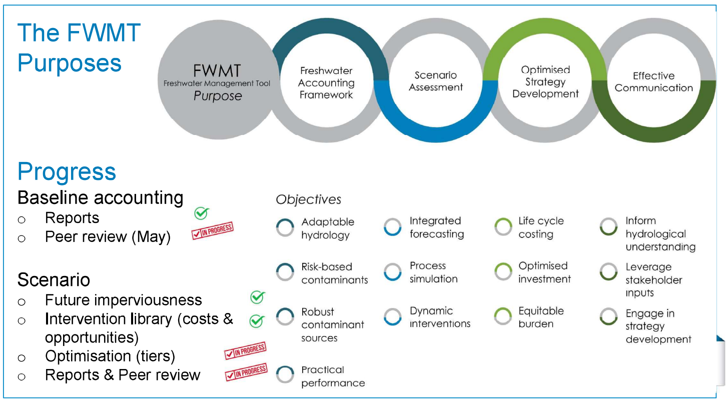
Integration
Modularity

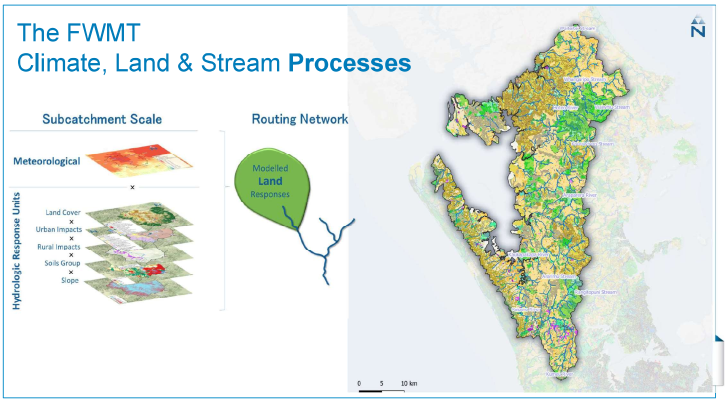
Selected models coupled



Climate change and N reduction scenarios







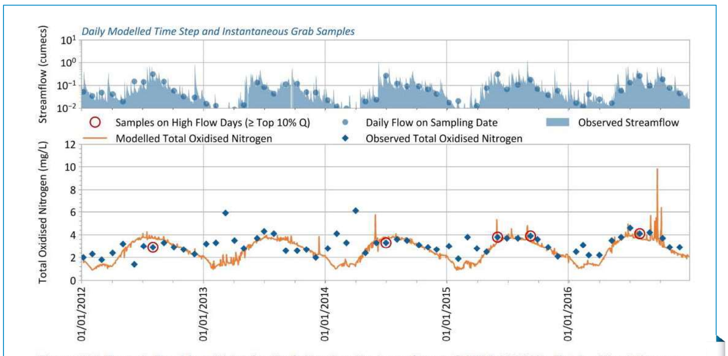
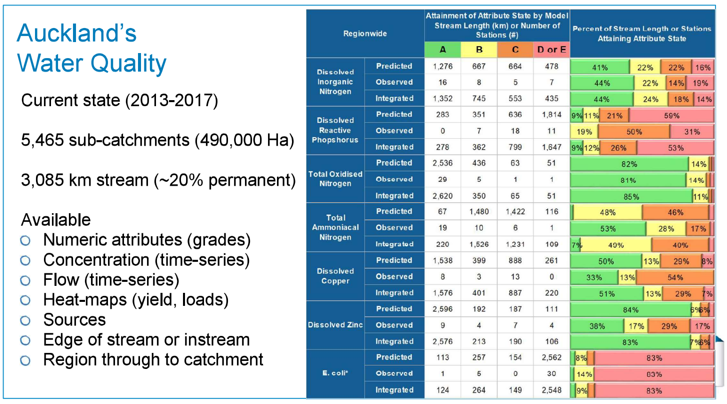
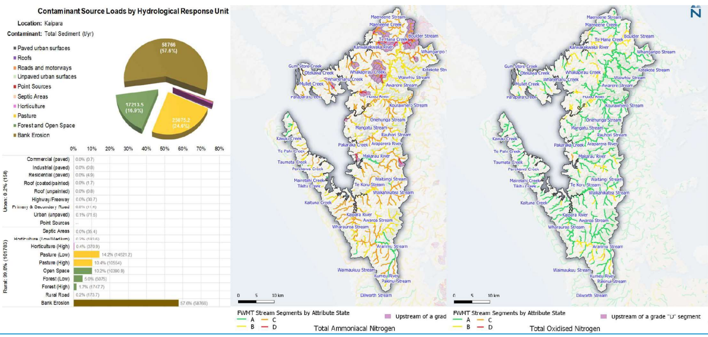


Figure 4-27. Example Panel from Water Quality Calibration: Ngakoroa Stream @ Mill Rd (43829) - Total oxidised nitrogen calibration: Simulated daily modelled time series vs observed grab sample concentrations.



Regionwide		Attainment of Attribute State by Model Stream Length (km) or Number of Stations (#) A	B	C	D or E	Percent of Stream Length or Stations Attaining Attribute State
Dissolved Inorganic Nitrogen	Predicted	1,276	667	664	478	41% 22% 22% 16%
	Observed	16	8	5	7	44% 22% 14% 19%
	Integrated	1,352	745	553	435	44% 24% 18% 14%
Dissolved Reactive Phopshorus	Predicted	283	351	636	1,814	9% 11% 21% 59%
	Observed	0	7	18	11	19% 50% 31%
	Integrated	278	362	799	1,647	9% 12% 26% 53%
Total Oxidised Nitrogen	Predicted	2,536	436	63	51	82% 14%
	Observed	29	5	1	1	81% 14%
	Integrated	2,620	350	65	51	85% 11%
Total Ammoniacal Nitrogen	Predicted	67	1,480	1,422	116	48% 46%
	Observed	19	10	6	1	53% 28% 17%
	Integrated	220	1,526	1,231	109	7% 49% 40%
Dissolved Copper	Predicted	1,538	399	888	261	50% 13% 29% 8%
	Observed	8	3	13	0	33% 13% 54%
	Integrated	1,576	401	887	220	51% 13% 29% 7%
Dissolved Zinc	Predicted	2,596	192	187	111	84% 6% 6%
	Observed	9	4	7	4	38% 17% 29% 17%
	Integrated	2,576	213	190	106	83% 7% 6%
E. coli*	Predicted	113	257	154	2,562	8% 83%
	Observed	1	5	0	30	14% 83%
	Integrated	124	264	149	2,548	9% 83%

Freshwater Accounting
Continuous, process outputs available regionwide (2013-17)



Scenario, Intervention & Optimisation
"Just farming transition" & "Improvement through growth"

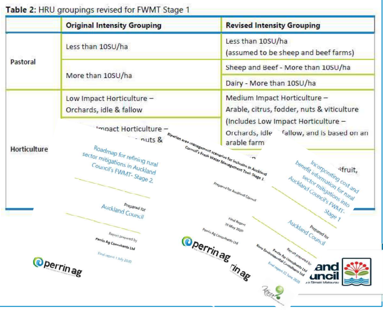
Future landscape (development)

Intervention library:
- Devices (wetlands, bunds, rain gardens, tree pits, swales, filter systems)
- Sources (good farm practices, green streets, soil conservation, retirement, inert roofing)

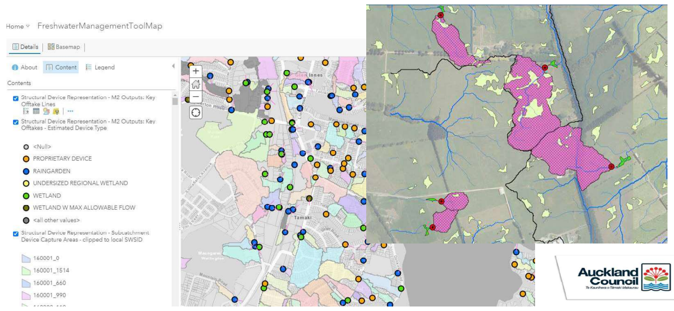
Life-cycle cost (50-yr discounted) – outlay, maintenance & renewal

Opportunity mapping (explicit GIS footprints)

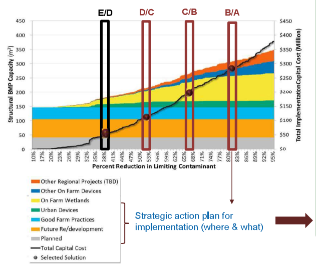
Multi-tiered optimisation
- Hydrology OR
- Contaminant(s) outcome AT
- Sub-catchment AND Coast



Scenario, Intervention & Optimisation
"Just farming transition" & "Improvement through growth"



Optimised & integrated catchment management
Fair, **efficient** & **effective**



Subwatershed ID	Metrics: % Load Reduction Critical Condition	Metrics: 24-hour Volume to be Managed (acre-ft)	Low-Impact Development: Ordinance	Low-Impact Development: Planned LID	Low-Impact Development: Public LID	Low-Impact Development: Residential LID	Streets: Green Streets, All Components	Regional BMPs: Regional BMPs (Very High)	Regional BMPs: Regional BMPs (High)	Regional BMPs: Private Regional BMPs	Total BMP Capacity (acre-ft)
103149	90%	19.78	0.53	0.89	2.33	1.54	4.29	0.00	0.00	8.87	18.4
103249	70%	117.58	2.38	0.04	4.61	2.97	39.83	14.82	22.76	4.22	91.6
103349	95%	16.65	0.33	—	0.37	0.47	2.95	0.00	3.29	5.93	13.3
103449	90%	94.21	2.70	—	1.10	5.81	18.01	0.00	0.00	50.52	78.1
103549	81%	8.66	0.74	—	0.11	1.44	0.24	0.00	0.00	5.83	8.4
103649	90%	45.73	0.76	—	0.57	1.07	9.12	0.00	0.00	26.08	37.6
103749	90%	21.52	0.63	1.09	0.65	1.92	2.83	0.00	0.00	11.38	18.5
103849	95%	12.71	0.90	—	—	1.31	0.35	0.00	0.00	8.31	10.9
103949	27%	1.43	0.36	—	—	1.26	0.69	0.00	0.00	1.36	3.7
104049	90%	7.15	0.21	—	0.74	0.31	1.45	0.00	0.00	3.34	6.0
104149	37%	0.94	0.22	—	—	0.76	0.52	0.00	0.00	0.00	1.5
104249	27%	0.40	0.19	—	—	0.62	0.17	0.00	0.00	0.00	1.0
104349	90%	10.46	0.33	—	0.02	—	1.82	0.00	0.00	6.13	8.3
104449	95%	5.18	0.55	—	11.96	0.85	0.13	0.00	0.00	2.82	16.3
104549	17%	0.22	0.34	—	—	—	0.08	0.00	0.00	0.00	0.4
Total	82%	362.6	11.2	2.0	22.5	20.3	82.5	14.8	26.0	134.8	314.1

RED = Subwatersheds with highest required % load reductions
BLUE = Subwatersheds with highest BMP capacities within a BMP category

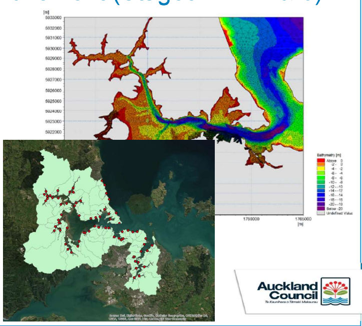
BE THE HOW.
WHAKAMAUA KIA TINA!

Prospects & Opportunities
FWMT 10-year continuous improvement (Stages 1 → 2 & 3)

Stage 1 expansion **occurring** or resourced:
- **Coastal** coupled modelling (FY20+)
- **Climate change** modelling (FY20+)
- **Lake** coupled modelling (FY20+)
- Ecological coupled modelling (FY21+)
- **FEP/Catchment remediation** (FY21+)
- Applied research (mesocosm, synoptic, paired)
- Cultural health index

Stages approach
- Pilots → Watershed/Harbour → Regionwide

Collaboration agencies
- University of Waikato
- NIWA, AgResearch & Manaaki Whenua LCR
- Kaipara Moana Remediation (MfE, NRC)



Freshwater Management Tool
Healthy Waters - IES

Summary
- Baseline (Current) State – complete & peer review
- Scenario & Optimised State – completion FY21

Flow & physicochemistry time-series for human, ecological & cultural health (rivers, lakes, coast)
1. Overview
2. Purpose
3. Baseline
4. Scenario, Intervention & Optimisation
5. Prospects (coastal, climate, lake, ecological, cultural)

Contact tom.stephens@aucklandcouncil.govt.nz or theodore.kpodonu@aucklandcouncil.govt.nz

PARADIGM ENVIRONMENTAL
HAL
MORPHUM ENVIRONMENTAL LTD
Koru Environmental Consultants Ltd
perrin ag

Auckland Council

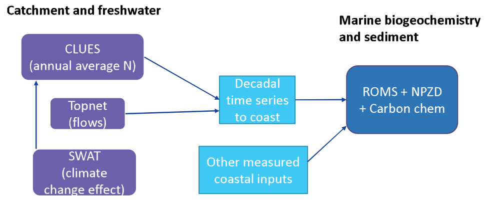
Hauraki Integrated Land-Water Modelling Workshop

Catchment models in pilot study

Sandy Elliott, Christian Zammit, Manawa Huirama, Linh Hoang

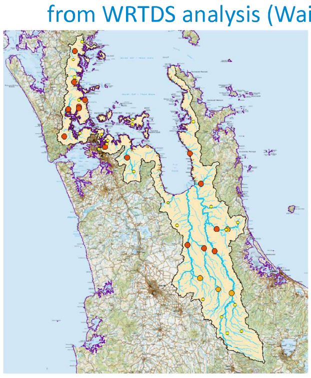
NIWA
Taihoro Nukurangi

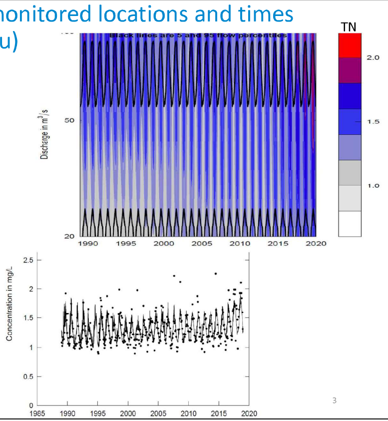
Selected models coupled



Climate change and N reduction scenarios

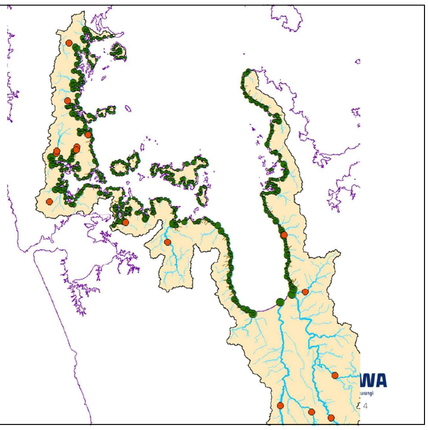
TN loads and time series at monitored locations and times from WRTDS analysis (Waihou)

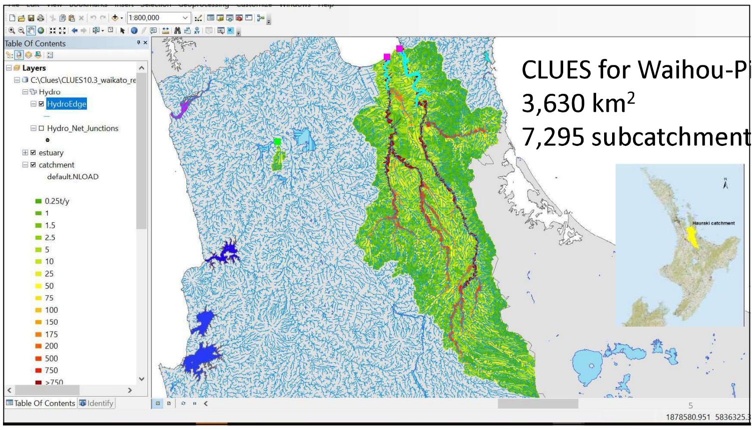




Extending beyond monitoring (spatially and in time)

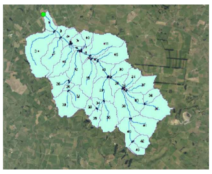
- Rating curves developed for sites with measurements, normalise flow
- Apply TopNet time series to rating curve from 'donor' site to get time series at 'recipient' site
- Rescale concentrations to match bias-corrected CLUES predicted load, including climate factor from SWAT
- Alkalinity, DOC, DO, HCO_3, pH from 44 monitored sites. Monitored means transferred to terminal segments.



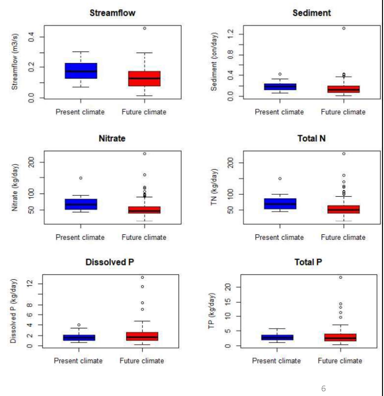


CLUES for Waihou-Pi
3,630 km^2
7,295 subcatchment

SWAT Climate change predictions at Toenepi (very early results)

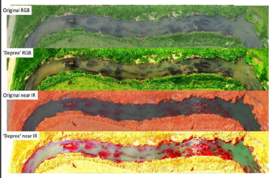


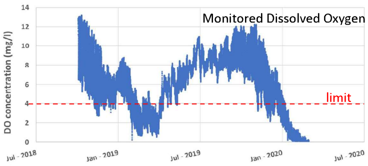
HadGEM2-ES model
RCP8.5 Emissions

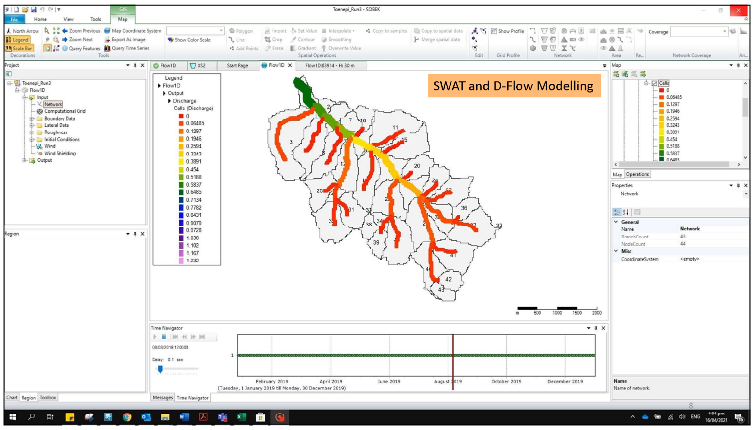


Coupled SWAT and Dynamic River Model Trial in Toenepi catchment

SWAT (daily flow and contaminant sources) → D-flow 1D (hydraulics) → D-Waq (Water Quality)







Next step?

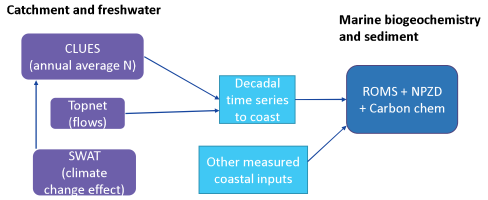
Catchment	River	Marine biogeochemistry and sediment
SWAT (daily flow and contaminant sources) →	D-flow 1D and D-Waq →	D-flow FM and D-Waq

Full catchment at REC resolution?
Mass erosion in sediment component?
GW model coupling?

ROMS Modelling of the Hauraki Gulf at NIWA

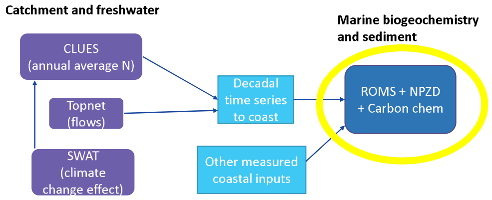
Helen Macdonald, Charine Collins, Joe O'Callaghan, Mark Hadfield, Graham Rickard, John Zeldis, Niall Broekhuizen, Sandy Elliot, Christian Zammit, Linh Hoang

Selected models coupled



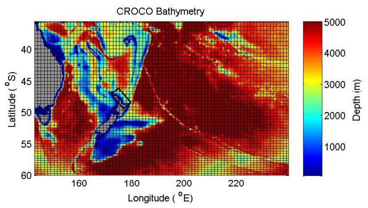
Climate change and N reduction scenarios

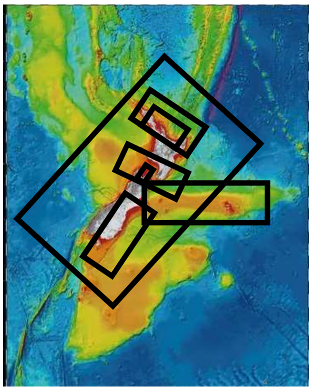
Selected models coupled



Climate change and N reduction scenarios

Aotearoa Regional Ocean Circulation Simulations (AROCS)





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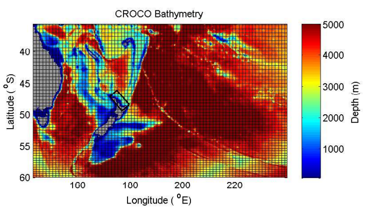
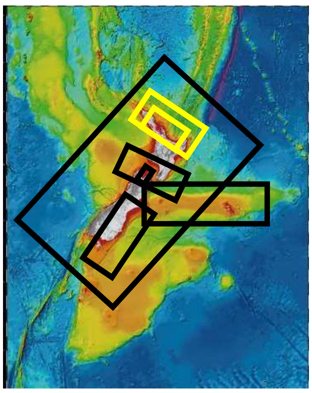
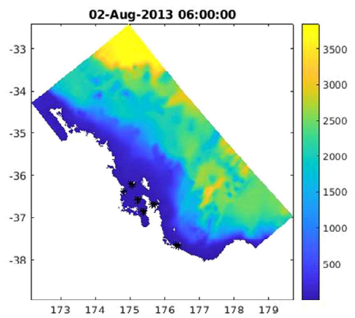
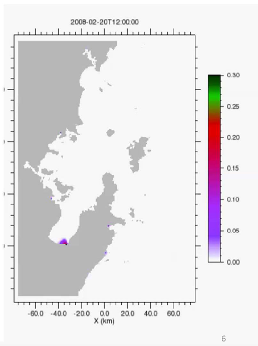




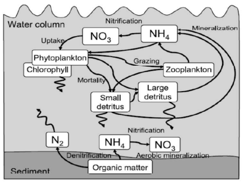
Hauraki Gulf physics: Rivers and connectivity



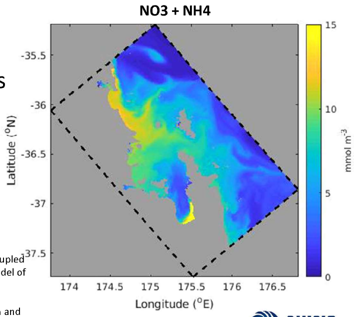


Biogeochemistry

- 750 m resolution grid
- Fennel model is used
- Can look at transport and changes in physical, biological and chemical properties

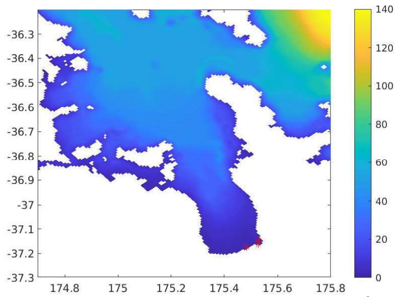


Fennel, K., et al. "A coupled physical-biological model of the Northern Gulf of Mexico shelf: model description, validation and analysis of phytoplankton variability." (2011).



Hauraki Integrated Land-Water Modelling

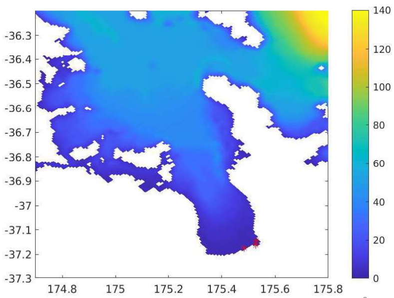
- Looking for a complete land to sea solution.
- Climate change is expected to bring changes to the system via land and oceanic pathways
- With coupled land and ocean models we can understand the system as a whole and as parts.



Climate, Freshwater & Ocean Science

Hauraki Integrated Land-Water Modelling

- We only had input from a small number of river inputs
- These were made using estimations and parameterisation
- Modelling of land-based interactions give us estimates of riverine inputs



Climate, Freshwater & Ocean Science

Hauraki Integrated Land-Water Modelling

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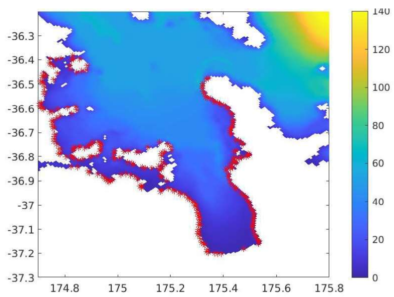
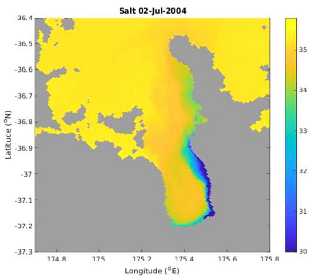
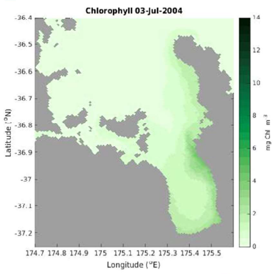


Climate, Freshwater & Ocean Science

Hauraki Integrated Land-Water Modelling

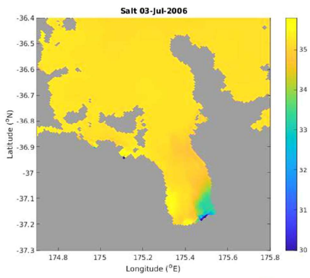




Climate, Freshwater & Ocean Science

Hauraki Integrated Land-Water Modelling

- Simulations for present day are setup
- They are currently running on the NESI supercomputer

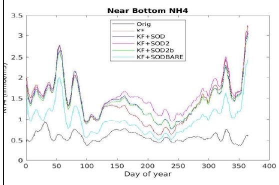


Watch this space …

- There are climate changes already locked in
- Changing weather pattern, and oceanic conditions are expected to affect HG – we have no control over these
- Future simulations can inform us on the effect of these on our system
- They can also determine how effective current management plans will be under climate change.
- The model is currently being setup for a future projection.
- It is estimated that we will have this at the end of this financial year.

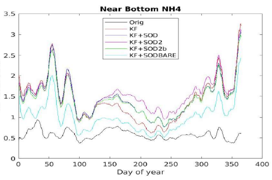
Other modelling Projects in the Hauraki Gulf

Improved Interactions with sediments

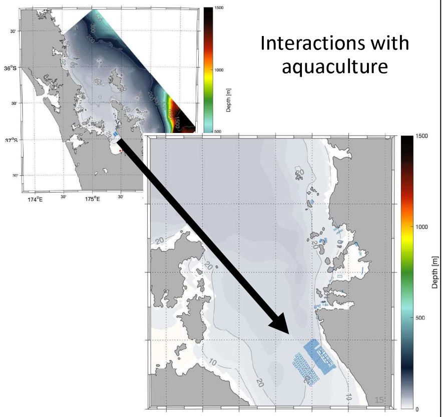


Other modelling Projects in the Hauraki Gulf

Improved Interactions with sediments

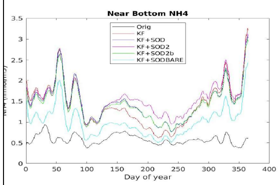


Interactions with aquaculture



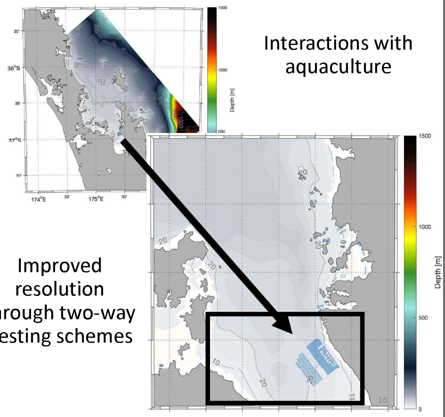
Other modelling Projects in the Hauraki Gulf

Improved Interactions with sediments



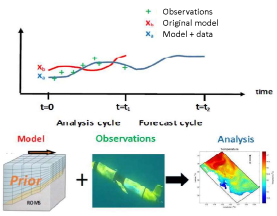
Interactions with aquaculture

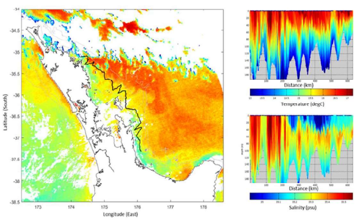
Improved resolution through two-way nesting schemes



Other projects in the Hauraki Gulf region: Data assimilation and individual events

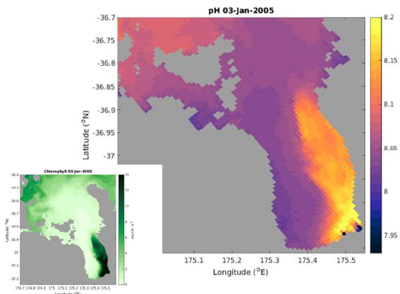
- The model predicts statistics of the ocean but individual events are not always captured well
- This method combines model and data to get a better estimate than the model with better coverage than the data





- Future work is to use Hauraki Gulf data and BGC in data assimilation

Other projects in the Hauraki Gulf region: Ocean Acidification and deoxygenation events



- Jesse Vance (Otago Uni) is using these model and data to investigate processes affecting pH in the Hauraki Gulf

Summary

- The models presented today present a coupled view of the ocean
- This model provides estimates of circulation, temperature, salinity, nutrients, phytoplankton, carbon and oxygen.
- A complete land to sea model will be useful in teasing out some of the different stressors affecting the system
- The model is almost complete with present-day simulations running now and future simulations in the pipeline

Delft3D & TELEMAC3D hydrodynamic models

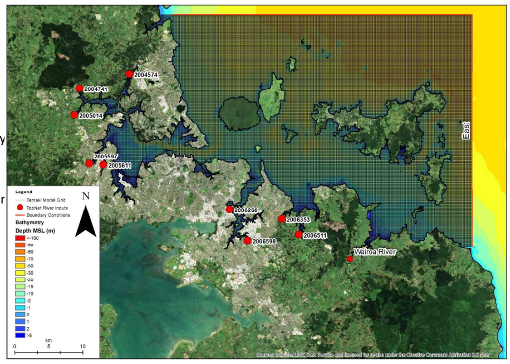
Hauraki Gulf and Tamaki Strait models

Glen Reeve, Andrew Swales, Richard Gorman, Niall Broekhuizen
Climate, Freshwater & Ocean Science

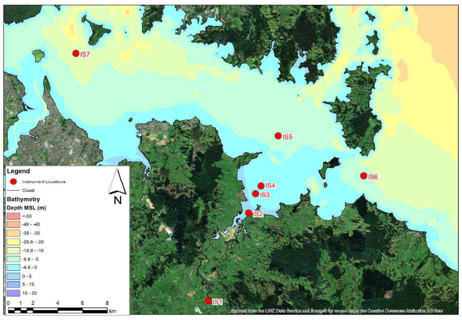
NIWA
Taihoro Nukurangi

Tamaki Strait

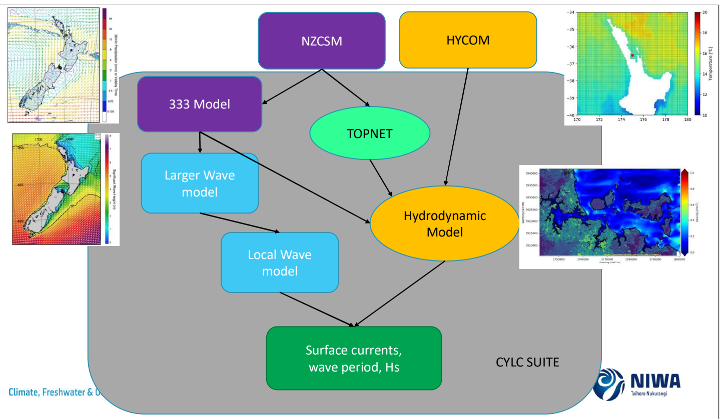
- Grid size 78 X 78 m
- 15 sigma layer
- NZCSM - Atmospheric coupling
- HYCOM temperature and Salinity offshore boundary
- TopNet catchment source flows
- Raw flow data from Wairoa River



Model Calibration and Verification

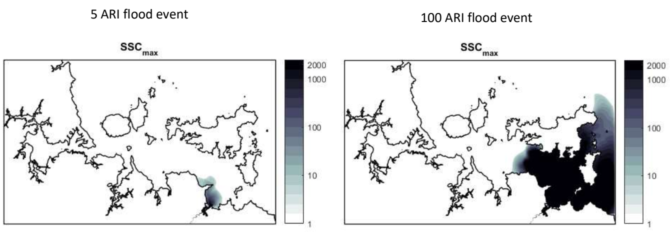


NIWA



NIWA

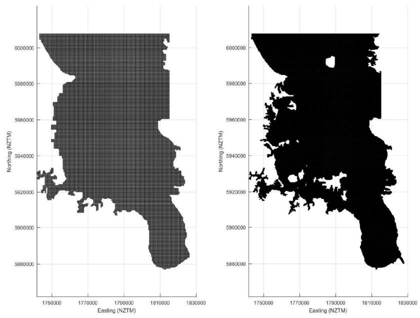
Wairoa River Sediment plumes



NIWA

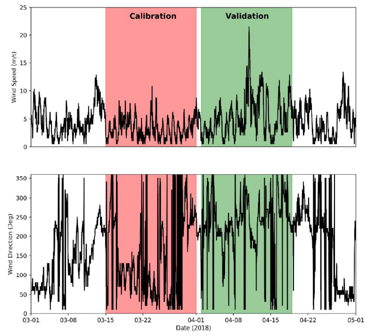
Hauraki Gulf

- Resolution
- Old model = 500 m
- New model = 250 m
- ROMS boundary conditions
- Water level, 3D (velocity, temperature and salinity).

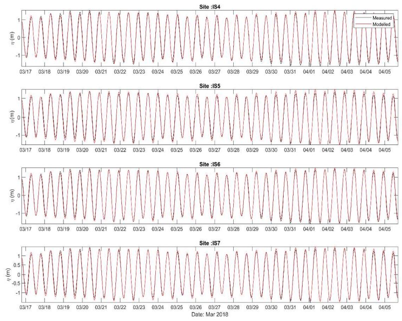


NIWA

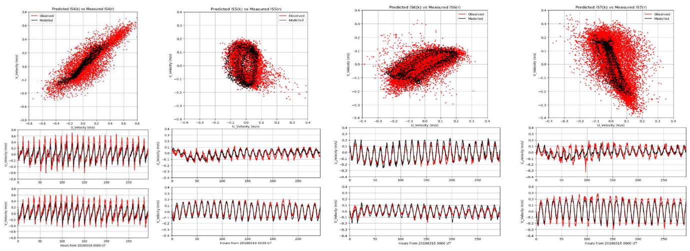
Calibration and Validation



Hydrodynamic model calibration



Calibration: Currents



Calibration - model performance statistics

Water levels

Sites	Bias	RMSE	Skill
IS4	-0.01	0.09	0.998
IS5	-0.05	0.104	0.996
IS6	-0.07	0.110	0.996
IS7	-0.04	0.088	0.997

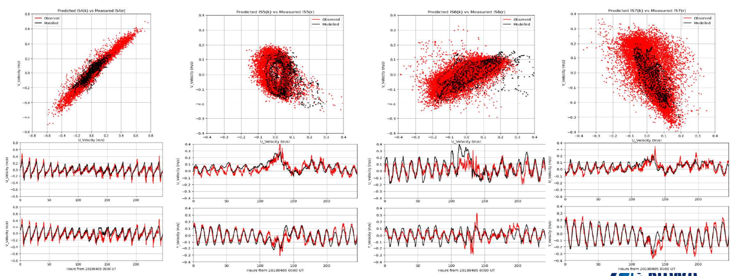
Current U - Velocity

Sites	Bias	RMSE	Skill
IS4	-0.04	0.10	0.94
IS5	0.008	0.035	0.9
IS6	0.017	0.044	0.96
IS7	-0.01	0.05	0.79

Current V - Velocity

Sites	Bias	RMSE	Skill
IS4	-0.004	0.1	0.94
IS5	-0.020	0.032	0.97
IS6	0	0.061	0.93
IS7	-0.008	0.04	0.97

Validation: Currents



Validation - model performance statistics

Water levels

Sites	Bias	RMSE	Skill
IS4	-0.01	0.088	0.996
IS5	0.020	0.110	0.992
IS6	-0.004	0.099	0.9946
IS7	0.014	0.097	0.994

Current U - Velocity

Sites	Bias	RMSE	Skill
IS4	-0.006	0.076	0.853
IS5	0.014	0.052	0.856
IS6	0.029	0.089	0.811
IS7	0.005	0.044	0.856

Current V - Velocity

Sites	Bias	RMSE	Skill
1S4	0.042	0.086	0.842
IS5	-0.013	0.045	0.912
IS6	0.002	0.061	0.803
IS7	0.012	0.056	0.943

Firth of Thames Sediment Transport

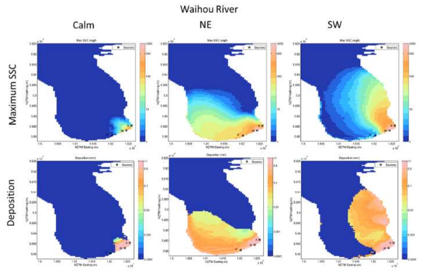
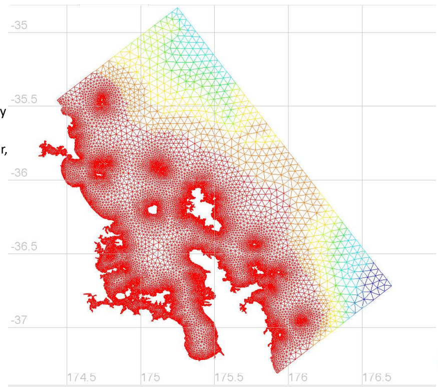
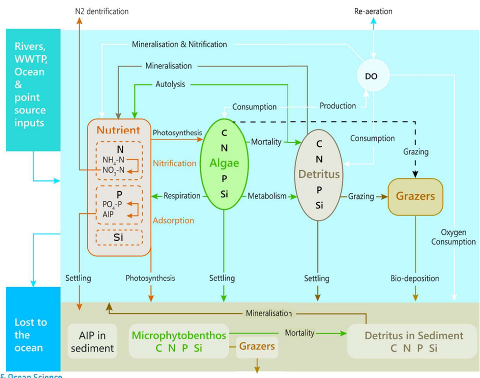


Figure 4-25: Maximum SSC (mg L^{-1}) and sediment deposition footprint (mm) extracted from the model for 3 wind conditions for the "event" (i.e., approximate 6-month ARI rainstorm) discharge from the Waihou River (W).

Hauraki Gulf

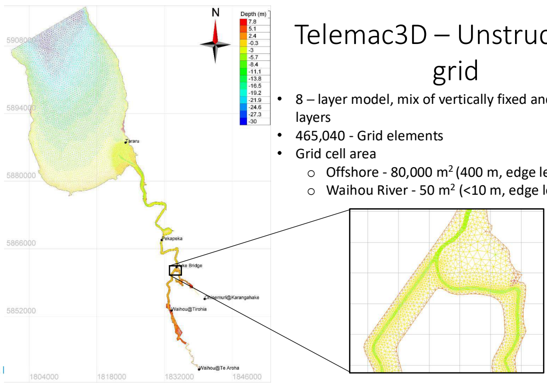
- **Delft3D Flexible Mesh**
- 20 sigma layer
- NZCSM - Atmospheric coupling
- HYCOM temperature and Salinity offshore boundary
- Raw flow data from Wairoa River, Waihou, Piako and Kauaeranga.



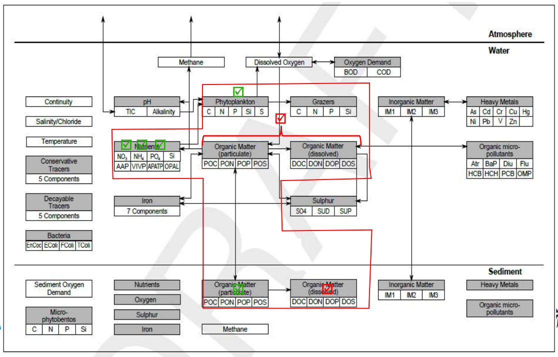


Telemac3D – Unstructured grid

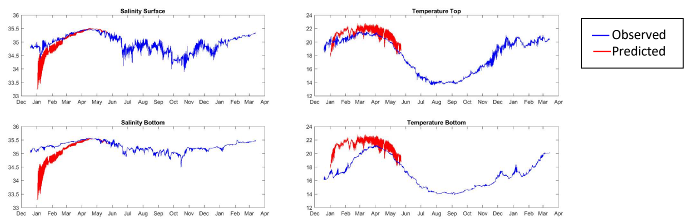
- 8 – layer model, mix of vertically fixed and sigma layers
- 465,040 - Grid elements
- Grid cell area
  - Offshore - 80,000 m^2 (400 m, edge length)
  - Waihou River - 50 m^2 (<10 m, edge length)



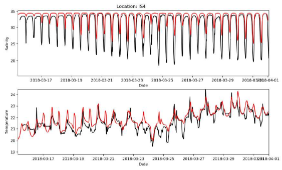
D-WAQ (water quality model)

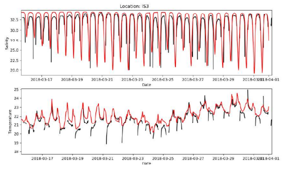


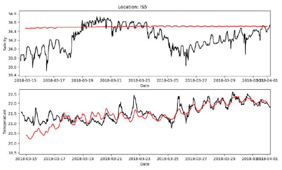
Hauraki calibration

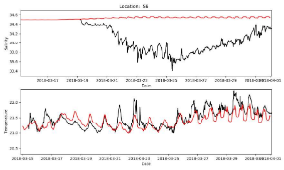


Temperature and Salinity









Thank you

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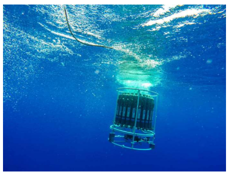
Climate, Freshwater & Ocean Science

NIWA's coastal observations in Hauraki Gulf / FoT

Charine Collins[1], John Zeldis[2], Joe O'Callaghan[1]

Charine.Collins@niwa.co.nz

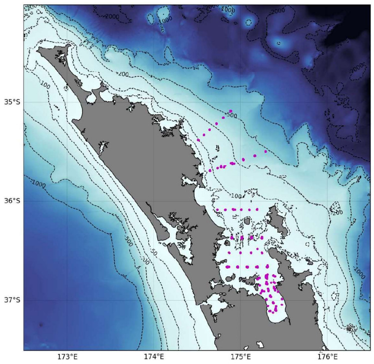


[1]National Institute for Water and Atmospheric Research, Wellington
[2]National Institute for Water and Atmospheric Research, Christchurch

Spatial Surveys

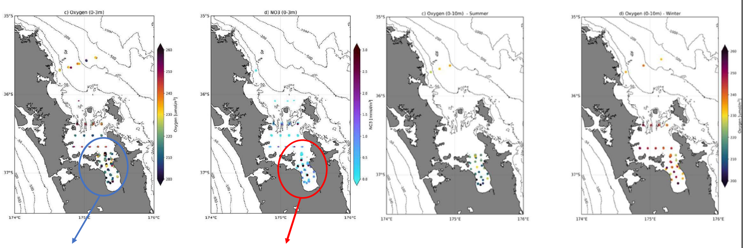
- 1996 – 2013
- 3 Seasons sampled on multiple occasions (Mar, Jul, Oct)
- Full depth CTDs
- Samples for pigments, nutrients etc. at selected depths
- Underway sampling of Chl-a, CDOM, pCO_2

Full Depth	Selected Depths
Temperature	Particulate carbon & nitrogen
Salinity	Particulate organic carbon & nitrogen
Oxygen	NO3
Fluorescence	NH4
PAR	Total dissolved nitrogen & phosphorous
	Dissolved reactive phosphorous
	Chl-a
	Dissolved reactive silica



Spatial Surveys

Spatial variability **Seasonal variability**



Lower oxygen concentrations compared to outer Hauraki Gulf

Higher NO3 concentrations compared to outer Hauraki Gulf

Lower O2 concentrations in summer

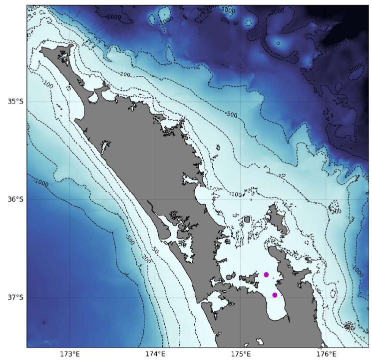
Higher O2 concentrations in winter

Long-term monitoring

- Outer biophysical mooring: 2002 - present
- Inner biophysical mooring: 2013 – present

- Temperature at multiple depths
- Salinity, oxygen, PAR at 2 depths (10m and 33m)

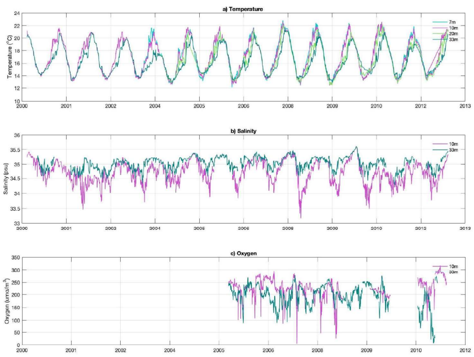
- 2005-2012: Current meters at 10m and 33m on outer mooring



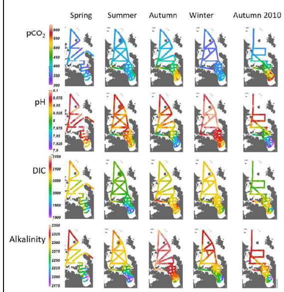
Long-term monitoring

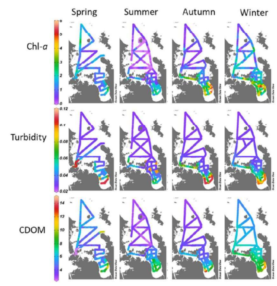
Long-term variability

- Seasonal cycle
- Long-term trends
- Extreme events



Drivers of acidification and hypoxia





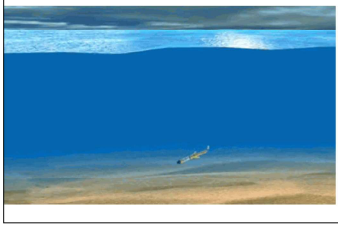
Carbonate, oxygen and primary production cycles are all intertwined and modulate the ecosystem stressors arising from catchment development

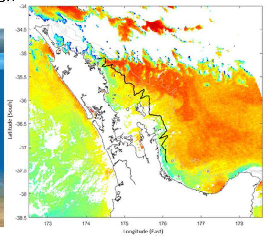
Zeldis et al. 2021, in prep

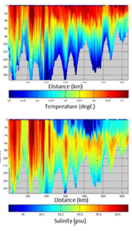
Gliders

- 2 Slocum gliders
- Buoyancy-driven autonomous underwater vehicles
- High-resolution physical and bio-optical measurements
- Profile the water column in a sawtooth pattern

- Temperature, salinity
- Chl-a fluorescence, CDOM, optical backscatter, PAR, DO





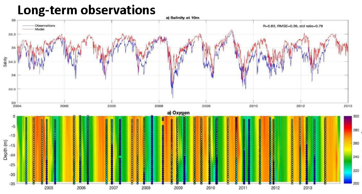


Courtesy of Joe O'Callaghan

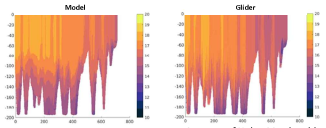
Observation-Model comparisons

Evaluate, calibrate and improve

Long-term observations

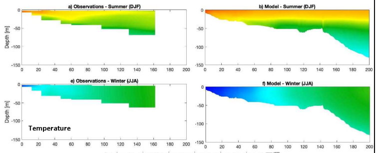


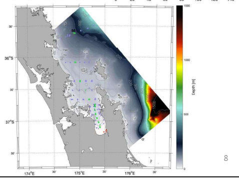
Gliders



Courtesy of Helen Macdonald

Spatial surveys





Need for observations

Need for observations

- New and improve understanding coastal system
- Monitoring of marine ecosystem
- Guide coastal model development and assessment
- Use models to connect and interpret sparse coastal observations
- Improve sub-seasonal to seasonal weather forecasts

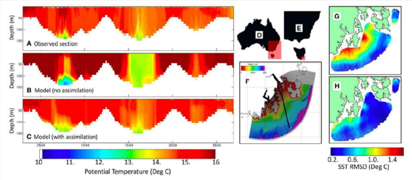


FIGURE 4 | Evaluation of gliders in the coastal sea south-eastern Tasmania using the Sparse Hydrodynamic Ocean Code and Ensemble OI (EnOI) data assimilation. Showing time series of potential temperature from **(A)** observations, and from the model with **(B)** no data assimilation (the control run) and **(C)** with data assimilation (the OSE run). The Model grid is shown in **(F)**, along with the model topography; with the grid location denoted by the red rectangles in **(D,E)**. A map of the RMS difference between the simulated and observed SST **(G)** without assimilation (the control run), and **(H)** with assimilation (the OSE run) are also shown. Adjusted from Jones et al. (2012).

Fuji et al. 2019, Front. Mar. Sci. 6:417

Looking forward

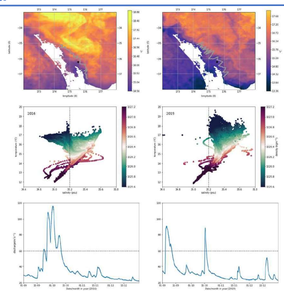
What is needed for models

- Physical variables (T, S, currents)
- Long-term biogeochemical variables (nutrients, oxygen, carbonate system)
- Flow and nutrients from rivers

Future observations

- Long-term moorings
- Spatial surveys (ship-based and/or gliders)
- Event scale observations

Partnership NIWA, Cawthron & regional councils



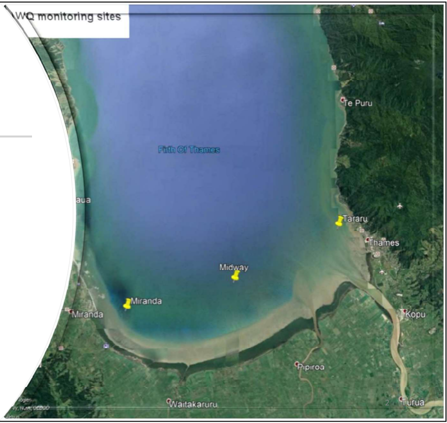
Courtesy of Joe O'Callaghan

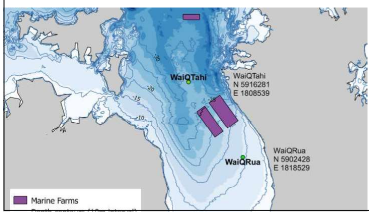
"...observations should sample the multiscale, two-way interactions of estuarine, nearshore, and shelf processes with open ocean processes..."
De Mey-Fremaux et al. 2019, Front. Mar. Sci. 6:436

Firth of Thames Water Quality Monitoring Programme

Previously…

- 3 sites
- Sampled monthly Jan – Dec 2007
- No long-term monitoring
- Low frequency for highly dynamic environment



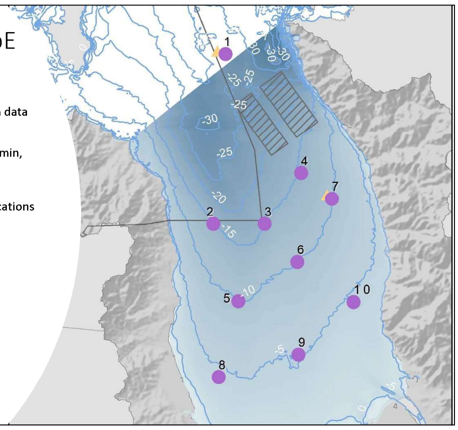


…enter buoys

- Collect high frequency monitoring data
- CTD, DO, Turb, Chl a, CDOM

Since May 2020 - New SoE monitoring programme

- Monthly sampling = monthly buoy verification data
- 2 buoys for continuous data approx. every 15 min, telemetered
- Discrete samples surface and bottom at 10 locations
- CTD + DO vertical profiles
- Depth integrated samples for microalgae and bacterial assessments



Samples /measurements for buoy verification at the following sites:

Wai-Q-Tahi (Site 1)

- **Seabird SBE 37 microcat (surface/ 1m)**
  - Salinity / Conductivity
  - Temperature
  - DO
- **Seabird SBE 16 inductive CT (8m)**
  - Salinity / Conductivity
  - Temperature
  - DO
  - Turbidity
  - Chlorophyll A
- **Seabrid SBE 37 inductive CT (20 m)**
  - Salinity / Conductivity
  - Temperature
  - DO

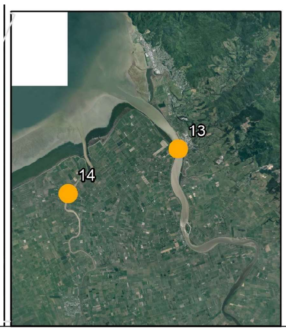
Wai-Q-Rua (Site 7)

- **Wetlabs WQMx**
  - Salinity / Conductivity
  - Temperature
  - DO
  - Chlorophyll A
  - Turbidity
  - Couloured dissolved organic matter (CDOM)

Discrete samples

- **UoO (NIWA):**
  - DIC/Alkalinity/pH (preserved in the field for later laboratory analysis)
- **Hills Lab:**
  - Turbidity (NTU and FTU)
  - Total suspended sediment (surface waters only)
  - Total nitrogen
  - Total ammoniacal nitrogen
  - Nitrate + nitrite nitrogen
  - Dissolved reactive phosphorus
  - Chlorophyll-a
  - Faecal coliforms
  - *Escherichia coli*
  - Enterococci
- **NIWA Hamilton:**
  - Phytoplankton (microscopic assay)
  - Bacteria (flow cytometry)
  - Total phosphorus
- **Field measurements at grab sample depth and continuous vertical profile from top to bottom:**
  - Temperature
  - Salinity / Conductivity
  - Turbidity (FNU)
  - DO

Since August 2020



Turbidity (NTU and FTU)
Total suspended sediment (surface waters only)
Total nitrogen
Total ammoniacal nitrogen
Nitrate + nitrite nitrogen
Dissolved reactive phosphorus
Chlorophyll-a
Faecal coliforms
Escherichia coli
Enterococci
Temperature
Salinity / Conductivity
Turbidity (FNU)
DO

Appendix B Mean concentration of other constituents

(shown on the next page)

Notes:

n before the constituent name denotes the number of samples
n is not given for $HC0_3$ for Auckland sites, because the concentration was derived from alkalinity.

SiteID	SiteName	Alkalinity (mg/L as CaCO3)	DOC (mg/L)	DO (mg/L)	HCO_3 (mg/L)	pH	n Alkalinity	n DOC	n DO	n HCO_3	n pH
6604	Matakana @ Wenzlicks Farm	49.3	3.52	8.55	59.1	7.31	29	26	330		448
6804	Mahurangi @ Warkworth Water Treatment Plant	48.1	3.51	9.44	57.8	7.59	29	26	284		361
6811	Redwood Stream @ Forestry H.Q.	43.3	2.90	9.51	52.0	7.39	29	26	310		366
7104	Waiwera Stream @ Upper Waiwera Road	44.7	3.97	9.09	53.7	7.34	28	25	329		455
7171	Nukumea @ Upper Site	26.0	3.04	9.15	31.2	6.92	24	22	91		143
7206	West Hoe @ Halls	29.2	1.71	9.33	35.0	7.11	27	25	201		253
7502	Okura Creek @ Awanohi Rd	45.9	6.01	8.39	55.1	7.30	28	26	194		246
7506	Vaughn Stream @ Lower Weir	64.8	6.07	7.34	77.7	7.15	28	26	210		257
7805	Rangitopuni River @ Walkers	43.3	7.14	7.90	52.0	7.25	26	26	243		326
7811	Oteha River @ Days Bridge	44.4	4.07	7.77	53.3	7.22	28	26	332		451
7830	Lucas @ Gills Road	49.1	4.01	8.26	58.9	7.36	28	26	313		365
7904	Opanuku Stream @ Candia Road Bridge	25.0	2.41	9.72	30.0	7.29	29	26	328		454
8110	Oakley Creek @ Carrington.	57.9	2.74	8.65	69.5	7.44	27	25	292		349
8205	Otara Stream @ Kennel Hill	55.3	4.23	7.28	66.4	7.34	28	25	330		387
8214	Otara @ East Tamaki Rd	33.5	2.45	9.73	40.2	7.35	28	25	317		454
8215	Pakuranga @ Greenmount Drive	164.2	4.66	7.43	197.1	7.55	28	25	317		379
8217	Pakuranga @ Botany Rd	61.4	3.39	11.60	73.7	7.66	28	25	318		379
8219	Otaki @ Middlemore Crescent	72.0	2.86	7.65	86.4	7.36	20	18	230		266
8249	Omaru @ Maybury Street	90.6	6.87	7.60	108.7	7.56	28	25	126		182
8516	Wairoa River @ Tourist Road	23.5	2.62	9.57	28.2	7.24	27	25	331		453
8568	Wairoa Trib @ Caitchons Rd	26.1	1.19	10.74	31.3	7.46	28	26	128		183
74401	Onetangi @ Waiheke Rd	39.6	2.32	8.27	47.6	6.99	25	25	81		121
74701	Cascades @ Whakanewha	21.7	2.32	9.82	26.1	7.17	25	25	79		120

SiteID	SiteName	Alkalinity (mg/L as CaCO3)	DOC (mg/L)	DO (mg/L)	HCO_3 (mg/L)	pH	n Alkalinity	n DOC	n DO	n HCO_3	n pH
1105_3	Waiau River at E309 Rd Ford	19.8	3.94	10.55	23.8	7.36	61	13	367	48	348
1122_18	Waihou River at Okauia	26.1	2.91	9.68	31.3	7.28	60	14	330	48	332
1122_34	Waihou River at Te Aroha	26.6	3.33	9.06	31.9	7.26	25	0	66	12	156
1122_41	Waihou River at Whites Rd	26.2	1.76	10.52	31.4	6.97	70	14	355	48	355
1173_2	Waiohotu Stm at Waiohotu Rd (Off SH5)	16.7	3.25	10.11	20.1	7.18	57	13	347	36	348
1174_4	Waiomou Stm at Matamata-Tauranga Rd	17.1	2.85	9.99	20.5	7.15	58	13	351	36	352
1230_1	Waitakaruru River (Hauraki Plains) at Coxhead Rd Br	33.3	6.56	9.23	40.0	7.23	48	13	329	36	330
1239_32	Waitekauri River at U	14.9	2.07	10.41	17.9	7.20	44	13	324	36	328
1249_15	Waitoa River at Landsdowne Rd Br	29.3	5.82	8.95	35.2	7.05	66	13	335	36	336
1249_18	Waitoa River at Mellon Rd Recorder	45.1	4.83	7.20	54.2	7.15	116	30	434	48	419
169_2	Hikutaia River at Old Maratoto Rd	17.8	3.42	9.90	21.4	7.12	37	13	320	36	320
234_11	Kauaeranga River at Smiths Cableway	13.2	3.32	10.15	15.9	7.11	61	13	357	48	349
489_2	Mangawhero Stm (Kaihere) at Mangawara Rd	25.7	4.15	10.07	30.9	7.37	48	13	316	36	315
619_16	Ohinemuri River at Karangahake	14.6	3.33	10.57	17.5	7.66	12	0	59	12	130
619_19	Ohinemuri River at Queens Head	14.5	3.24	10.43	17.4	7.20	36	13	343	36	345
619_20	Ohinemuri River at SH25 Br	12.5	2.51	10.37	15.0	7.07	38	13	338	36	341
669_6	Oraka Stm at Lake Rd	31.2	2.97	9.35	37.5	7.23	58	13	397	36	398
749_10	Piako River at Kiwitahi	35.6	5.30	8.70	42.7	7.08	105	13	379	37	379
749_15	Piako River at Paeroa-Tahuna Rd Br	37.6	8.29	8.39	45.1	7.20	116	13	369	48	368

Appendix C Source contributions

Name	Load (t/year)	Percent	Cumulative Percent	Area	Yield
Waihou River	2934.43	41.57	41.57	1982.87	18.9
Piako River	2223.64	31.50	73.08	1481.99	18.4
Waitakaruru River	266.19	3.77	76.85	165.50	16.1
Wairoa River	183.48	2.60	79.45	262.42	7.0
Rosedale WWTP	173.00	2.45	81.90		
Rangitopuni Stream	56.75	0.80	82.70	97.80	7.6
Kauaeranga River	44.63	0.63	83.34	129.13	4.7
Mahurangi	38.58	0.55	83.88	57.26	10.8
Henderson Creek	33.87	0.48	84.36	59.24	5.7
Orere River	33.27	0.47	84.83	43.81	7.6
Puhoi River	33.26	0.47	85.30	47.13	7.1
Matakana River	27.04	0.38	85.69	23.02	11.7
Waiwera River	26.76	0.38	86.07	34.19	7.8
Otara Creek	22.77	0.32	86.39	28.57	6.4
Karito Canal	21.82	0.31	86.70	10.62	20.6
Weiti Stream	18.62	0.26	86.96	16.11	11.6
Manaia River	18.53	0.26	87.22	47.51	3.9
Brigham Creek	18.21	0.26	87.48	21.74	8.4
Makomako Stream	18.20	0.26	87.74	27.86	6.5
Not in Topomap	17.95	0.25	87.99	17.68	10.2
Waikawau River	17.28	0.24	88.24	33.72	5.1
Waiau River	16.49	0.23	88.47	31.80	5.2
Hauarahi Stream	15.87	0.22	88.70	12.70	12.5
Miranda	15.83	0.22	88.92	13.60	11.6
Umangawha Stream	15.25	0.22	89.14	22.19	6.9
Lucas Creek	13.14	0.19	89.32	23.88	5.3
Matakana River	12.47	0.18	89.50	16.13	7.7
Whitford Stream	12.36	0.18	89.68	5.28	23.4
Orewa River	11.81	0.17	89.84	9.59	12.3
Te Mata River	11.57	0.16	90.01	27.14	4.3
Other	705.30	9.99	100.00	1982.87	18.9