Maketū Estuary

Numerical Modelling to Support Healthy Environments

Bay of Plenty Regional Council

Report 44801501

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The expert in **WATER ENVIRONMENTS**

Maketū Estuary

Numerical Modelling

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1 Executive Summary

Bay of Plenty Regional Council commissioned DHI to develop numerical models of Maketū and Waihī Estuaries. The hydrological and biological modelling is aimed at determining acceptable levels of catchment derived nutrients, sediment and bacteria flowing into Waihī and Maketū Estuaries that would support a healthy environment, particularly in terms of ecological functioning and integrity that align with the values and needs of the local and wider community.

The objectives of the integrated estuarine hydrological and biological modelling of Maketū and Waihī Estuaries include assessment of:

- Bacterial levels and spatial abundance, and to determine limits to meet guidelines for shellfish gathering waters and for the bathing water quality guidelines,
- Sedimentation and water clarity, and to determine loads for acceptable deposition rates that will support defined macrofaunal diversity and abundance for a healthy and productive benthic ecosystem,
- Nutrient loads and spatial extent of macroalgae and seagrass, and to determine loads to match defined ecological health grades.

Numerical modelling was carried out with sufficient resolution and accuracy to reliably inform each of the above assessments.

The present report exclusively focuses on Maketū Estuary. It includes a description of the numerical modelling approach, input data and validation techniques applied for this study area, and details the results of the numerical models.

Input data for the models were obtained from the previously calibrated SOURCE catchment models which include four sources of catchment flows and loads into the Maketū Estuary with the most significant source being the Kaituna River[1].

Three scenarios were modelled – Baseline (representing the state of Maketū Estuary in 2014), Scenario 1 (Naturalised state), and Scenario 2 (Scenario C+M1).

Baseline scenario represents the best estimate of catchment, land use, land management practices and estuarine conditions as it was in 2014.

Scenario 1 scenario represents the estuarine condition that would exist if the catchments were under natural vegetation, with no water take and no contaminant discharges from human activities in the catchment. However, historical anthropogenic changes to the natural river channels still remain.

Scenario 2 is a potential future scenario based on credible future land and water use and land management practice changes. This scenario is an exploratory one in that it does not pose a solution about what future land use should be but can be used to inform the planning process. It assumes good management practice, land use change, increased kiwifruit on land suitable for growing, and increased areas of mānuka and plantation forest on steeper uplands.

[1] Location of the three sources within Maketū Estuary is presented in Figure 4-4 (Section 4.1.3).

Summary of the assessments for the three scenarios is provided below -

- **Sedimentation assessment**:

  Care has to be taken when interpreting the results from the sedimentation modelling, since the estuary is establishing a new morphological balance since the re-diversion of the Kaituna River was completed.

  Scenario 1 is characterised by a reduction of approximately 70% of the sediment loads from the Baseline Scenario. This scenario provide an understanding of what the estuarine conditions would have been prior to extensive land clearing and modification.

  Scenario 2 includes the combined effect of future land use and management practices leading to an increased sediment load of approximately 20% over the Baseline Scenario.

  The modelling indicates that Scenario 2 will have a small (but still undesirable) impact on predicted sedimentation rates within the estuary, while Scenario 1 produces a significant reduction in the sedimentation rates within the harbour.

- **Bacterial assessment**:

  For the Baseline scenario, catchment loads of E.cocci and F.coli into Maketū Estuary amounted to 7.74×10^{14} cfu/yr, and 1.1×10^{15} MPN/yr respectively.

  For Scenario 1, the loads are 4.8×10^{14} cfu/yr for E.cocci and 6.6×10^{14} MPN/yr for F.coli.

  In Scenario 2, the loads are 6.7×10^{14} cfu/yr for E.cocci and 9.4×10^{14} MPN/yr for F.coli.

  In all three scenarios, the loads from the Kaituna River contributed more than 90% of both the E.cocci and F.coli loads from the catchment to Maketū Estuary.

  In Maketū estuary, the predicted median E.cocci levels across the estuary meet the guideline[2] value of 280 cfu/100 ml in all three scenarios.

  The predicted 95th percentile E.cocci levels meet the guideline value across most of the estuary in all three scenarios.

  E.cocci levels do not meet the guideline value only near the catchment sources in the south east region of the estuary for the Baseline and Scenario 2 simulations.

  Based on analysis at 95th percentile level, a 20.39% reduction of baseline catchment loads is required for E.cocci levels across the whole estuary to meet the guideline value.

  In the estuary, the predicted median F.coli levels meet the guideline[3] value of 14 MPN per 100 ml in most of the estuary[4] for all three Scenarios.

  Model results indicate that F.coli levels meet guideline for most of the estuary during Summer in Scenario 1. However, they do not meet guideline value across most of the estuary during winter for all three Scenarios.

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[2] Microbiological Water Quality Guidelines state that for estuaries to be safe for primary contact recreation/bathing, the concentration of E.cocci must not exceed 280 cfu/100ml.

[3] For Kaimoana to be safe to eat, the median faecal coliform content of water samples taken over a shellfish-gathering season shall not exceed a Most Probable Number (MPN) of 14/100 mL, and not more than 10% of samples should exceed an MPN of 43/100 mL (using a five-tube decimal dilution test).

[4] Figure 5-17 in the Section 5.2 of the report shows the different regions of Maketū Estuary.

Based on analysis at 50th percentile level, a 38.87% reduction of baseline catchment loads is required for F.coli levels across the whole estuary to meet the guideline value.

- **Nutrient and ecological assessment**:

  For the Baseline scenario, Total Nitrogen (TN) and Total Phosphorous (TP) inflows from the four sources into Maketū Estuary amounted to 1140 tonnes/year and 49.1 tonnes/year respectively.

  In Scenario 1, loads into Maketū Estuary are 366 tonnes/year of TN and 24.2 tonnes/year of TP.

  In Scenario 2, loads into Maketū Estuary are 699 tonnes/year of TN and 41.5 tonnes/year of TP.

  The Kaituna River contributed between 91% and 99% of the annual loads of TN, and 94% to 96% of the annual loads of TP to Maketū Estuary in all three simulation runs.

  TN loads to Maketū Estuary in winter ranged from 34-37% of the total annual load while summer loads range from 17-20% of the total annual load in all three runs.

  TP loads to Maketū Estuary in winter loads ranged from 27-35% of the total annual load while summer loads ranged from 19-23 % of the total annual load in all three runs.

  As per the recommended guidelines for macroalgal-dominated estuarine systems[5], potential TN concentration in the estuary should be less than 0.055 mg/l for the estuary to be categorize to Trophic State Band A (near reference), between 0.055 mg/l and 0.18 mg/l for the estuary to be categorized to Trophic State Band B (slightly impacted), between 0.18 mg/l and 0.35 mg/l for the estuary to be categorized to Trophic State Band C (moderately impacted), and above 0.35 mg/l for the estuary to be categorized to Trophic State Band D (heavily impacted).

  As per these guidelines;

  - For the Baseline scenario , the predicted median concentration of TN is above 0.35 mg/l across the estuary. This categorizes Maketū Estuary to Trophic State Band D (heavily impacted).
  - For Scenario 1, the predicted median concentration of TN is between 0.055 mg/l and 0.18 mg/l for most of the estuary. This categorizes Maketū Estuary to Trophic State Band B (slightly impacted).
  - For Scenario 2, the predicted median concentration of TN is above 0.35 mg/l in most of the estuary. This categorizes Maketū Estuary to Trophic State Band D (heavily impacted).

  Based on the model results, about 52% or 64% reduction in Baseline TN catchment loads (median) is required for Maketū Estuary to achieve max-Band C or mid-Band C Trophic State respectively. About 75% or 84% reduction in Baseline TN catchment loads (median) is required for Maketū Estuary to achieve max-Band B or mid-Band B Trophic State respectively.

  The total mass of Total Nitrogen deposited across the estuary is predicted to be 59.7 tonnes/year, 43 tonnes/year, and 59.3 tonnes/year for the Baseline, Scenario 1, and Scenario 2 simulations respectively.

[5] Ministry for the Environment. 2021. A guide to setting instream nutrient concentrations under clause 3.13 of the National Policy Statement for Freshwater Management 2020. Wellington: Ministry for the Environment.

The amount of Nitrogen efflux (from the sediment to water column) is predicted to be 17 tonnes/year, 11 tonnes/year, and 15 tonnes/year for the Baseline, Scenario 1, and Scenario 2 simulations respectively.

The total mass of Total Phosphorous deposited across Maketū estuary is predicted to be 7.7 tonnes/year, 5.8 tonnes/year, and 7.5 tonnes/year for the Baseline, Scenario 1, and Scenario 2 simulations respectively.

Model results indicate that achieving a TN:TP ratio of 30:1 (a relevant standard for assessing nutrient limitation[6]) is not feasible across most of the estuary for the given catchment loadings in all the three scenario runs. It can be inferred that Maketū Estuary is therefore Nitrogen limited and will be sensitive to increases in nitrogen levels.

In the estuary, the 95th percentile spatial distribution of Chlorophyll-a levels in the water column shows that predicted levels are higher than 8 µg/L in the Baseline and Scenario 2 simulations in the eastern region of the estuary. Levels lower than 2 µg/l are observed in Scenario 1 across the estuary.

The predicted median macroalgae wet weight is between 200 and 250 g/m^2 across the estuary for all the three simulation runs. This categorizes Maketū Estuary to Band C for ecological quality based on NZ Estuary Trophic Index Screen Tool 2[7].

In Maketū Estuary, macroalgae abundance levels are predicted to be higher in central portion of the estuary. This portion carries higher levels of nitrogen and phosphorous deposition in the sediment layer. Resuspension of these deposited nutrients could play a role in causing elevated macroalgae growth in the central portion of the estuary.

In Maketū estuary, in all three runs, seagrass spatial extent is predicted to be higher in eastern portion as compared to the rest of the estuary.

The abundance levels of seagrass are predicted to increase in both Scenario 1 and Scenario 2 as compared to the Baseline simulation results.

Reduction in light attenuation is predicted in both scenarios. It is higher in Scenario 1 as compared to Scenario 2 across most of the estuary.

Sedimentation results indicate that the central area of the estuary is characterised by clay and silt deposition. There is minimal sand deposition observed in this area.

As a combination of stressors including nutrient loadings, light availability, presence of sand, sediment organic enrichment, and competition from macroalgae affect seagrass growth in Maketū estuary, restorative actions which address these stressors are recommended.

[6] Park, S.G. 2018: Setting interim guidelines for nutrient loads to Maketū and Waihī Estuaries. BOPRC internal memo, Objective ID-A2984492.

[7] Robertson, B.M., Stevens, L., Robertson, B., Zeldis, J., Green, M., Madarasz-Smith, A., Plew, D., Storey, R., Oliver, M. (2016b) NZ Estuary Trophic Index Screen Tool 2. Determining Monitoring Indicators and Assessing Estuary Trophic State. Prepared for Environlink Tools Project: Estuarine Trophic Index: 68.

2 Introduction

The Bay of Plenty Regional Council (BoPRC) is implementing a planning process to address the cumulative effects of land use on the receiving environment water quality.

As part of this process, BoPRC have commissioned DHI to undertake the numerical modelling of the Maketū and Waihī Estuaries (see Figure 2-1) with the aim to determine acceptable levels of catchment derived nutrients, sediment and bacteria that would support a healthy environment for both estuaries, particularly in terms of ecological functioning and integrity that align with the values and needs of the local and wider community.

To allow a better understanding of the hydrodynamic and biological processes affecting each estuary, outcomes of this study are divided into two reports.

The present report exclusively focuses on Maketū Estuary. It includes a description of the numerical modelling approach, input data and validation techniques applied for this study area, and details of the model results.

The Waihī Estuary assessment is presented in the first report (DHI, 2021).

Figure 2-1 Map of Maketū and Waihī Estuaries

2.1 Project Scope

The National Policy Statement for Freshwater Management (NPS-FM) requires Regional Councils to implement freshwater objectives, limits and methods to achieve sustainable freshwater quality and quantity in the region. It also requires Regional Councils to consider the connectivity between freshwater and coastal waters and assess limits in the freshwater domain required to protect the values of estuarine receiving environments. In addition, BoPRC are implementing a planning process which aims to understand the cumulative effects of land use on receiving environment water quality and values based on a holistic mountains to the sea approach.

As part of that planning process, BoPRC has identified that the Maketū and Waihī, are sensitive to catchment inflows. The catchments of both Maketū and Waihī Estuaries have historically undergone extensive drainage and intensification of land use that result in relatively high sediment and nutrient loads.

Both these estuaries have been assessed to be sensitive to the quality of their respective freshwater inflows and are in a moderate to poor state. The poor ecological health and high risk of degradation of the estuaries is attributed to eutrophication and sedimentation.

To quantify the conditions that will support a healthy environment within the Maketū and Waihī Estuaries, BoPRC commissioned DHI to carry out numerical modelling to quantify estuarine conditions and determine levels of loading that would result in an acceptable estuary state.

This modelling assessment includes the following components.

Bacteria Load Assessment:

Maketū and Waihī Estuaries are identified as having significant cultural values and as such should meet standards for kai moana to be safe for consumption.

E.cocci is the indicator used for bathing in marine waters. To meet safe primary contact recreation and bathing standards, the recommended concentration of E.cocci is 280 cfu/100ml.

F.coli is the indicator used for the shellfish gathering waters. For Kaimoana to be safe to eat, the median faecal coliform content of water samples taken over a shellfish-gathering season shall not exceed a Most Probable Number (MPN) of 14/100 mL, and not more than 10% of samples should exceed an MPN of 43/100 mL (using a five-tube decimal dilution test).

Modelling has been used to determine the level of reduction in bacteria loads required to reach the desired water quality objective.

Sediment Load Assessment:

High levels of suspended sediments and deposition in estuaries have substantial implications for aquatic ecosystems and natural habitats. Sediments carry significant amounts of organic matter, pollutants, and heavy metals that may be deposited either within areas acting as sinks for fine-sediments or areas offshore of estuary systems.

Sediment resuspension increases turbidity, reducing light penetration and contributes to the total nutrient load both of which impact seagrass growth.

Field survey assessments of the Maketū and Waihī estuaries indicate that sedimentation has historically contributed to ecological degradation, impacted on biological diversity, functioning and kai moana values.

The Client's Coastal Environment Plan has an objective to reduce sediment accumulation in harbours and estuaries over time compared to 2014 levels. However, it is not certain if reducing future loads to below those occurring in 2014 will lead to improvements in estuary health, or whether much higher load reductions may be required to achieve this.

Sediment modelling has been carried out to determine the changes in sedimentation that may occur under the scenarios considered. The modelling provides an insight into inherent complexity of the estuary and its connections to different sediment sources in the catchment.

Nutrient Load Assessment:

Eutrophication is the result of the excessive input of nutrients from surrounding catchments (point source and diffuse), which then causes excessive algal growth and subsequent changes in the functioning of biological, chemical and physical processes of shallow coastal ecosystems.

In New Zealand's shallow and sheltered estuarine systems, particularly those with high flushing rates and short water residence time, it is more likely for blooms of macroalgae to occur. These blooms lead to the accumulation of high algal biomass which then causes increased organic enrichment, deoxygenation, increases in toxic sulphide levels and increases in mud content of the sediments. All of these changes are detrimental to benthic biological assemblages which may be lost and replaced by less diverse opportunistic pollution tolerant species.

Both Maketū and Waihī Estuaries are impacted by nutrient loading, which is expected to result in high eutrophication. Surveys show algae accumulation in the estuaries because of sufficient nutrients loading to sustain algae growth and little flushing of algae from the estuary.

Nutrient modelling will help inform the setting of appropriate limits on nutrient loads to keep Maketū and Waihī Estuary in a healthy ecological state that supports biodiversity, ecological functioning, mahinga kai, taunga ika and other cultural values. The modelling approach determines where, and to what extent, eutrophication issues could be expected to occur.

Ecological Assessment:

Seagrass habitats in estuaries are adversely affected by at least three primary mechanisms, including indirect light limitation (from sediment resuspension and algal shading), the direct toxicity of excessive nutrients, and unfavourable environmental biogeochemical alterations.

Surveys have shown large areas of the Maketū Estuary to be highly degraded due to dense accumulations of macroalgae, thus impacting the ecosystem serviced provided by the estuary for birds, fishing, shellfish gathering and biodiversity.

Studies have shown that reasonably dense algal accumulations occurred over a third of the Maketū Estuary. The dense algal accumulations also cause very low concentrations of dissolved oxygen (DO) at night in the estuary, resulting in anoxic muds and a loss in the abundance and diversity of shellfish and other benthic fauna.

Ecological modelling has been used to investigate the dynamics of macroalgae and seagrass growth.

2.2 Objectives of Proposed Study

The specific objectives of the study were:

1. Optimise the three-dimensional hydrodynamic model previously developed for Kaituna re-diversion consenting to simulate the estuarine dynamics over a 1-year period and ensure good model performance.

2. Include the up-to-date Kaituna River re-diversion design and recently collected wetland bathymetry data into the three-dimensional hydrodynamic model.

3. Assess bacterial levels and their spatial variability. Determine limits in the estuary and the associated catchment to meet guidelines for shellfish gathering waters and for the bathing water quality guidelines.

4. Assess sedimentation and water clarity, and determine acceptable deposition rates in the estuary and associated loads from the catchment that will support defined macrofaunal diversity and abundance for a healthy and productive benthic ecosystem

5. Assess nutrient loads and spatial extent of macroalgae and seagrass and determine loads in the estuary and the associated catchment to meet acceptable macroalgal coverage and seagrass extent in the estuaries to match defined ecological health grades.

2.3 Coordinate System and Vertical Datum

For this study, all data is presented using the New Zealand Transverse Mercator (NZTM) projection and the vertical datum is referenced to Moturiki Mean Sea Level Datum.

2.4 Scenario Overview

Three scenarios are modelled as follows.

Baseline: Scenario representing the state of Maketū Estuary in 2014

This scenario represents the best estimate of catchment, land use, land management practices and estuarine conditions as it was in 2014.

Scenario 1: Naturalised State Scenario

The scenario represents the estuarine condition that would exist if the catchments were under natural vegetation, with no water take and no contaminant discharges from human activities in the catchment. However, historical anthropogenic changes to the natural river channels still remain.

Scenario 2: Mitigation M1 + Development Scenario C (M1C)

The last scenario is a potential future scenario based on credible future land and water use and land management practice changes. This scenario is developed by BOPRC in conjunction with industry and community groups (with advice from Perrin Ag Consultants and Landcare Research) during the development of the eWater SOURCE catchment models. This scenario is an exploratory one in that it does not pose a solution about what future land use should be but can be used to inform the planning process. Scenario M1C generally included land use change to wetlands in the lowland areas (in line with predicted sea-level rise over the next 40 years), increased kiwifruit on land suitable for growing, increased areas of mānuka and plantation forest on steeper uplands, and assumed good management practice.

3 Overview of Data to Support Hydrodynamic Model Development

This section describes the measurements used to setup, force and/or validate the hydrodynamic and biological numerical models used in this study.

3.1 Bathymetry Data

In the previous study, the coastal model bathymetry was produced using both 2x2 m lidar data and chart data from MIKE C-MAP (DHI, 2017). No changes were applied here.

Regarding the Kaituna River model, the resource consent model bathymetry was produced by combining 2 by 2 m resolution LIDAR data (Figure 3-1) and the Kaituna re-diversion channel design (Figure 3-2). In addition, recently collected LIDAR data over the wetland areas (Figure 3-3) were incorporated into the model.

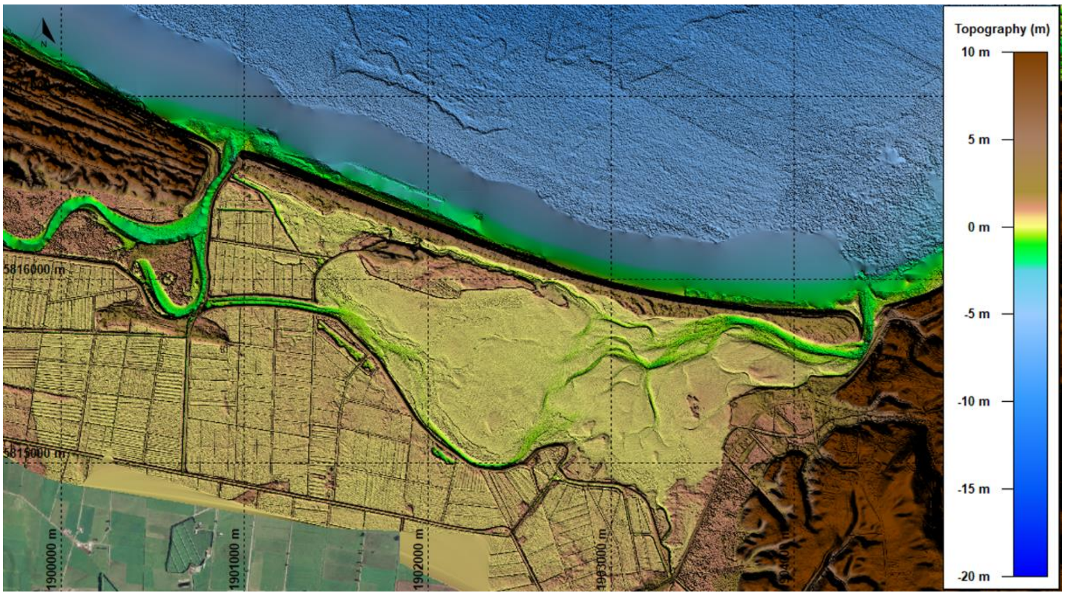

Figure 3-1 LIDAR data collected by Fugro in 2013 in the Maketū region including both Maketū and Waihī Estuaries, and Kaituna River (Moturiki Vertical Datum).

Figure 3-2 Deepened Kaituna re-diversion channel design (Moturiki Vertical Datum).

Figure 3-3 Recently collected drone survey topography data over wetlands adjacent to Kaituna River re-diversion (Moturiki Vertical Datum).

4 Numerical Modelling Approach

This section provides an overview of the numerical modelling approach with regard to predicted:

- bacterial levels and spatial abundance;
- sediment and water clarity; and
- nutrients loads and spatial extent of macroalgae in Maketū Estuary.

It includes a detailed description of the hydrodynamic, sediment transport and biological model setups, input data, post-processing and calibration/validation.

4.1 Hydrodynamic Model

A nesting approach was adopted to capture hydrodynamics over the Maketū Estuary and Kaituna River regions. A two-dimensional hydrodynamic MIKE21 model including open-ocean offshore boundaries was applied to generate the boundary conditions at both the estuary and the river entrances. Boundary conditions were subsequently used in a nested three-dimensional hydrodynamic (MIKE3) model to adequately represent the mixing of fresh and salt waters at the re-diversion interface, which was then used as upstream boundary for a final 2D model of the estuary.

Model setups, domain and bathymetry, boundary conditions and atmospheric forcing are all detailed in the following Sections.

4.1.1 Model Setup

MIKE 21/3 FM models were built using the previous calibrated 3D model version developed for the Kaituna River re-diversion design and assessment required to gain resource consent (DHI, 2014). Upgrades of the model aimed to optimise the flexible mesh to maintain an acceptable computational time for the running the models over one year.

The final design for the constructed re-diversion, was different than what was investigated for resource consent, including a wider Fords Cut re-diversion channel in the estuary, and a different configuration of culverts between the estuary and the river. These changes were incorporated into the new model. The bathymetry was also updated with new survey data over the Papahikahawai channel and the adjacent wetlands to account for the post-re-diversion environment.

Details of the physics and numerical schemes used in MIKE3 and MIKE21 FM are provided in DHI (2020a) and DHI (2020b).

As outlined in DHI (2020c), 2014 was identified as the representative year for modelling.

4.1.2 Domain and Bathymetry

Multiple nested 2D/3D models were used to represent the physics influencing the Maketū Estuary dynamics adequately while maintaining a reasonable computational time for the simulation of mud transport and water quality over Maketū Estuary.

A parent 2D HD model including Bay of Plenty, Kaituna River and Maketū Estuary was used to generate the boundary conditions at the Kaituna and Maketū estuary mouths. Corresponding model grid and bathymetry are shown in Figure 4-1.

Then, a nested 3D HD model (Child 1) including 5 vertical layers was applied to accurately capture the saltwater intrusion through the Kaituna River up to the re-diversion channel and Maketū Estuary. This model domain (Figure 4-2) only included both the Kaituna River and Maketū Estuary. The HD model was forced using the boundary conditions from the 2D parent model.

Data from the three-dimensional model at the culvert and at the estuary mouth was used to force a 2D model (Child 2) which included the Bay of Plenty and the Maketū Estuary as shown in Figure 4-3.

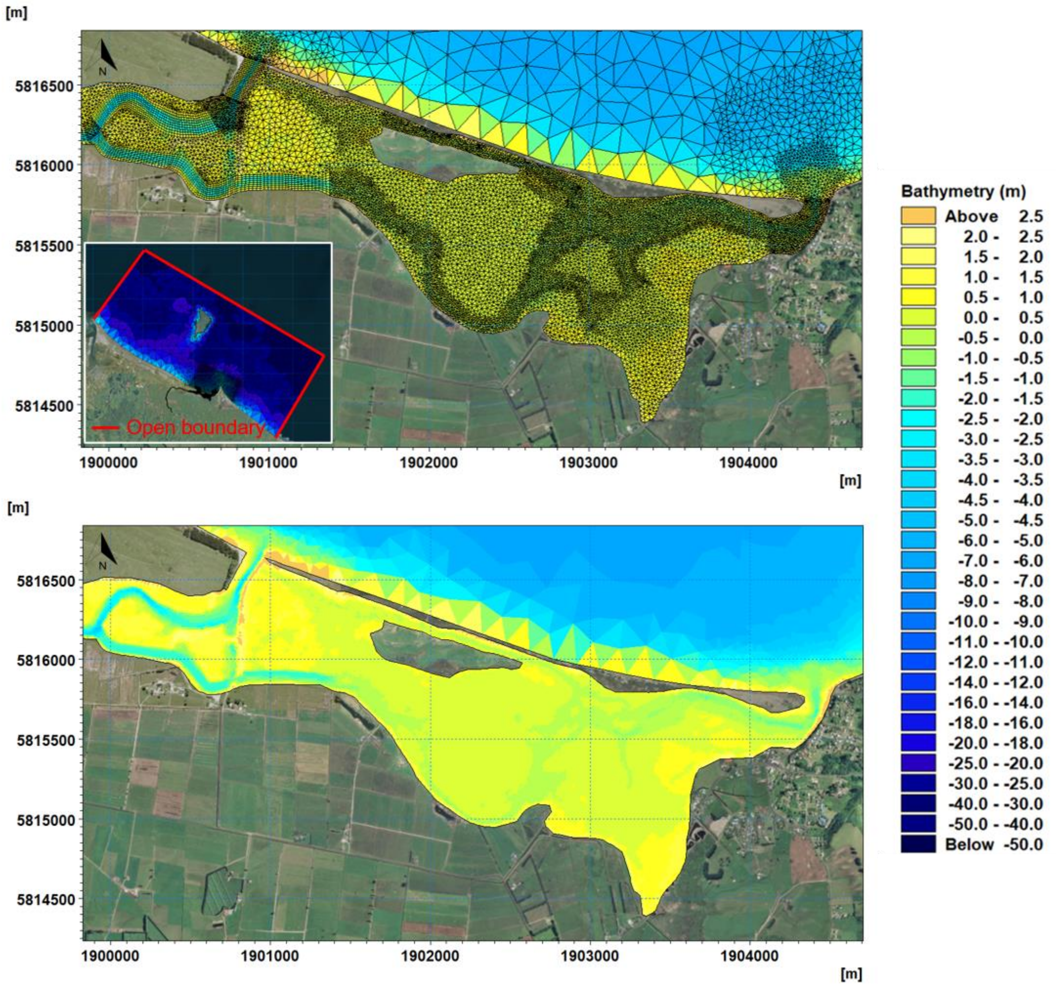

Figure 4-1 Parent model grid and bathymetry over the Bay of Plenty and Maketū Estuary used in MIKE21 two-dimensional model.

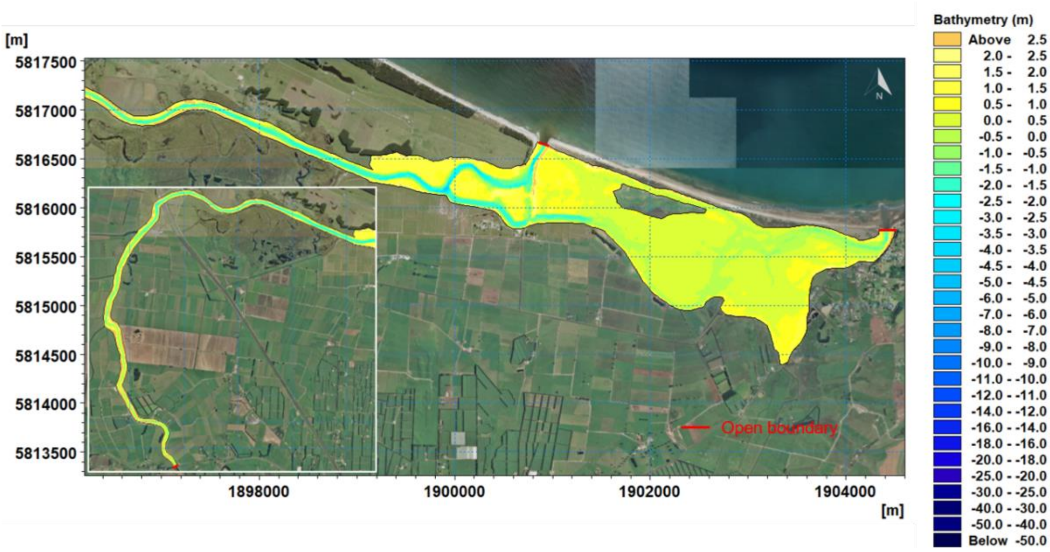

Figure 4-2 The high resolution Child 1 model grid and bathymetry over the Maketū Estuary and Kaituna River used in MIKE 3 three-dimensional model.

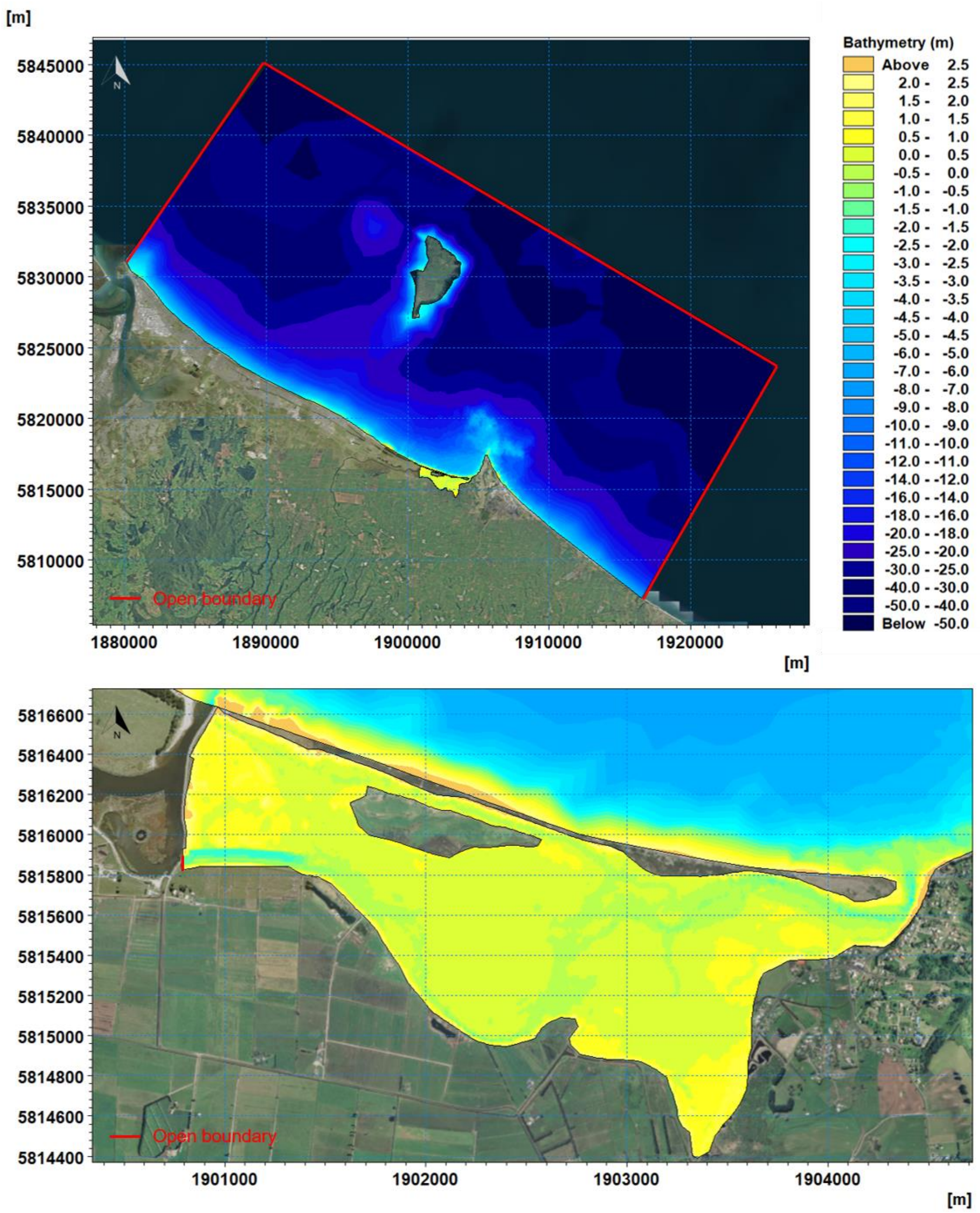

Figure 4-3 Child 2 model grid and bathymetry the Bay of Plenty and Maketū Estuary used in MIKE21 two-dimensional model.

4.1.3 Boundary Conditions and Sources

Open-boundary conditions over Bay of Plenty were setup using the Flather formulation (Flather, 1976) which combines tidal water elevation and current velocities extracted from the DTU10 global ocean tide model (Cheng and Andersen, 2010). Ocean temperature and salinity were setup at the open boundaries using the global HYCOM analysis (Cummings, 2005).

Discharge flows associated with the Kaituna River and the three other catchment sources (see Figure 4-4) were defined in the hydrodynamic model using the catchment data provided by WWLA (2020). Kaituna River temperatures were set up from measurements. Note that in the absence of measurements of stream water temperature, the water temperature for Sources 56, 58 and 59 were defined using the Kaituna River temperature.

Timeseries of the Kaituna river and source discharge flows are presented in Figure 4-5 and Figure 4-6, respectively. Timeseries of water temperature and salinity are shown in Figure 4-7 and Figure 4-8.

Figure 4-4 Location of the three smaller catchment sources within Maketū Estuary.

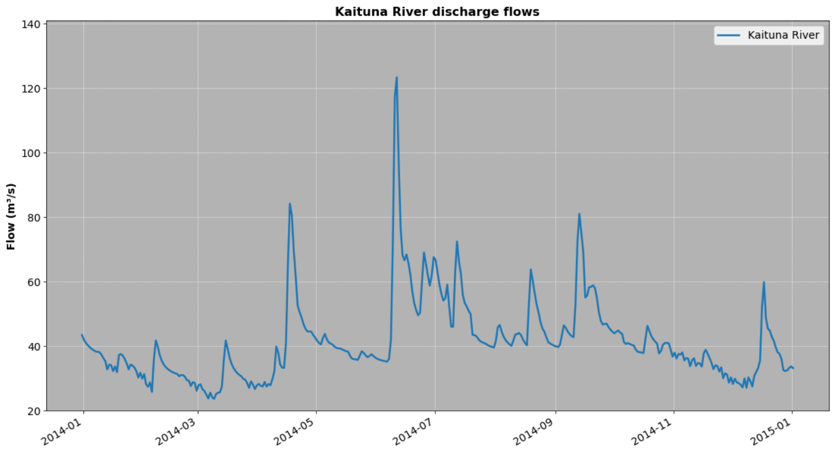

Figure 4-5 Kaituna River discharge flows over 2014 estimated from River Lake (2018).

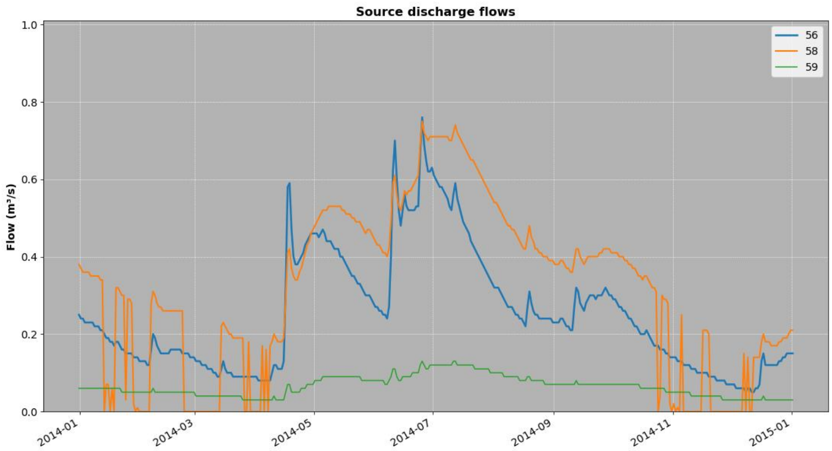

Figure 4-6 Discharge flows over 2014 associated with sources 56, 58 and 59 located within the Maketū Estuary. Flows were estimated using catchment data provided by WWLA (2020).

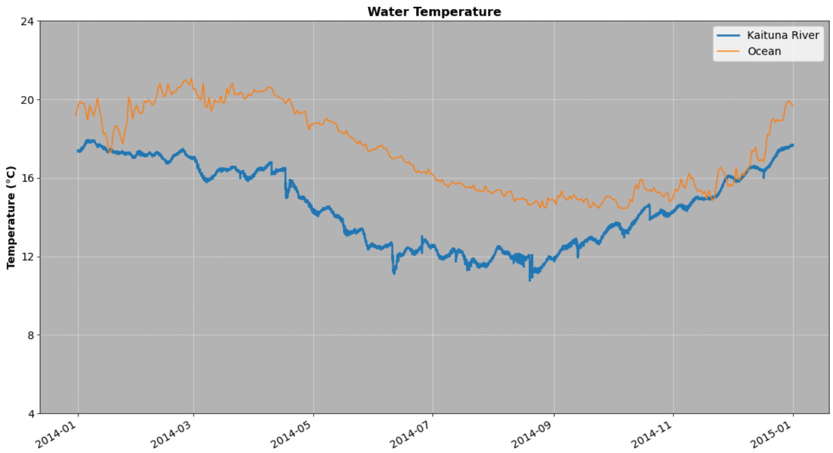

Figure 4-7 Measured Kaituna River and HYCOM offshore water temperature over 2014.

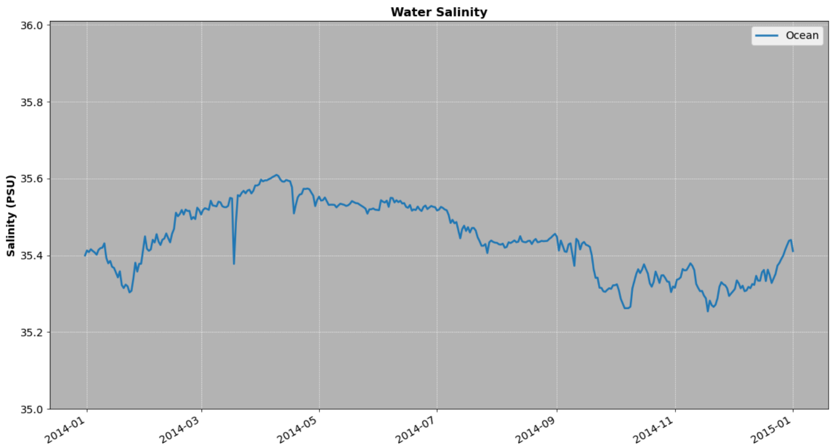

Figure 4-8 HYCOM offshore water salinity over 2014.

Because the scope of the present study was focused on the transport of catchment derived sediments, and the limited fetch within the estuary itself, no wave modelling was carried out.

4.1.4 Atmospheric Forcing

While only tidal forcing were used during the calibration and validation phase (See Section 4.1.6), space-constant wind velocities were applied in the annual simulation. For this purpose, measured wind data at Mount Maunganui were rescaled using short-term historical wind data recorded at Maketū Estuary from March 26th to April 22nd, 2020. Corresponding wind roses and timeseries are presented in Figure 4-9 and Figure 4-10, respectively.

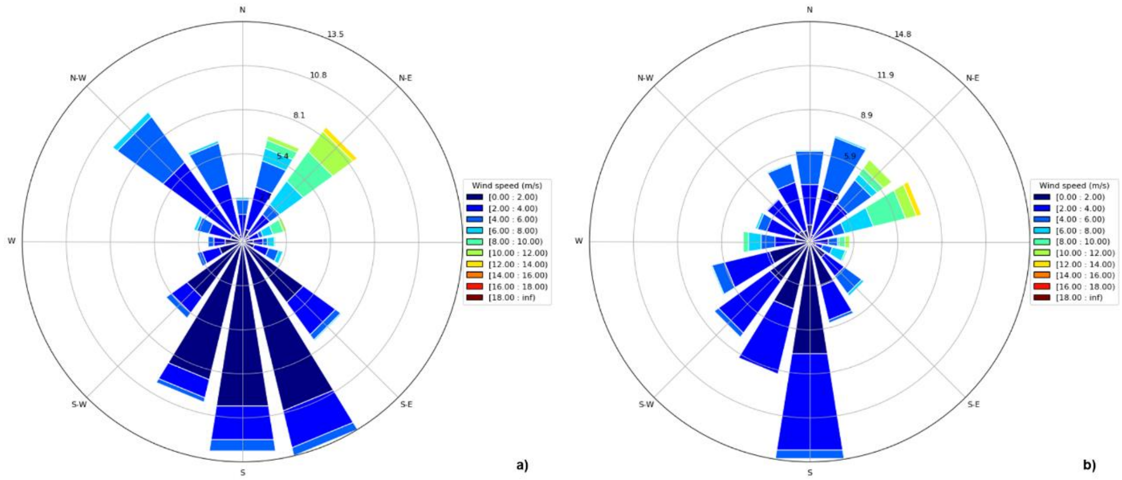

Figure 4-9 Measured and rescaled wind roses at Maketū Estuary (a) and Mount Maunganui (b)

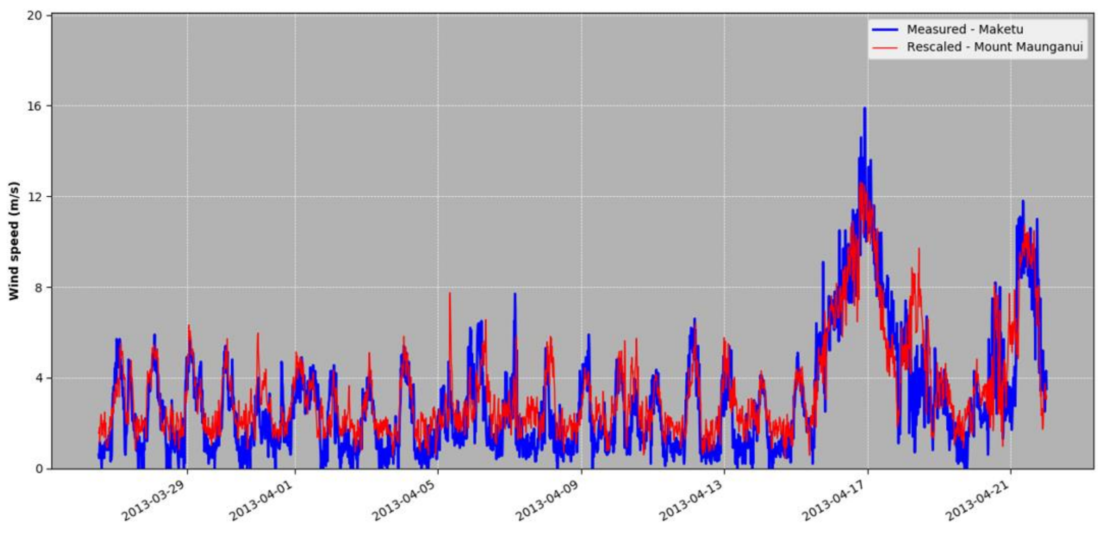

Figure 4-10 Timeseries of measured and rescaled wind speed at Maketū Estuary and Mount Maunganui, respectively.

4.2 Mud Transport Model

MIKE 21 Mud-Transport (DHI, 2020d) was used to simulate the transport of clay, silt and sand particles over Maketū Estuary while hydrodynamics were prescribed from the decoupled MIKE 21 HD model (Child 2) presented in Section 4.1.

4.2.1 Model Setup

Bathymetry and forcing were all derived from MIKE 21 HD outputs. Sediment fractions, concentrations and settling velocities were setup in MIKE 21 MT based on both the catchment model outputs (see Section 4.2.1.5) and suspended sediment samplings (see Section 4.2.1.1). Details of the MT model are provided in this section.

4.2.1.1 Suspended sediment fractions

In absence of suspended-sediment samples in the Kaituna River, sediment fractions were defined in the model based on the samplings carried out in the Waihī Estuary (DHI, 2021).

Five sediment fractions from clay to medium sand particles were therefore considered in the present modelling. For each discharge source in the model, the respective sediment fractions were applied as follows:

- 5% of clay
- 55% of silt
- 24% of very fine sand
- 11% of fine sand
- 5% of medium sand

4.2.1.2 Particle settling velocities

The transport of sediment particles is driven by the hydrodynamics into the receiving water environment and the settling velocity of each particle. Settling velocities vary based on their size, shape and density. Flocculation effects between mud and sand greatly influence these parameters over time, making the settling velocity of each particle dynamically variant. Because it is impossible to predict the settling velocity of every particles over time, averaged settling velocities corresponding to a specific population of particles are generally applied in sediment transport models. This approach aims to capture the representative behaviour of a population, in this case, each sediment fraction. An average settling velocity obtained from Ferguson and Church (2004) was defined in the model for each sediment fraction as shown in Table 4-1. This approach does not account for turbulent or flocculation mechanisms driven by the mud/sand ratio or the mixing between fresh and salt waters. Potential impacts of the modelling approach in terms of predicted results are discussed in the report on Waihī Estuary (DHI, 2021).

Table 4-1 Settling velocities for each sediment fraction included in the mud transport modelling.

Sediment fraction	Settling Velocity (mm/s)
Clay	0.1
Silt	0.5
Very Fine Sand	5.0
Fine Sand	10.0
Medium Sand	15.0

4.2.1.3 Critical shear stress for deposition and erosion

The deposition of suspended sediment is the transfer of sediment from the water column to the bed. Deposition takes place where the bed shear stress is smaller than the critical shear stress for deposition. A value of 0.07 N/m^2, used as default in MIKE 21 MT was setup over the domain.

The critical bed shear stress for erosion that defines the threshold above which each fraction of sediment is resuspended, was setup to 0.1 N/m^2. In a mixed-bed composition environment characterised by high percentages of cohesive (mud) and non-cohesive (sand) sediments, the estimation of this threshold is normally determined during calibration. In absence of sediment transport measurements, a mid-range value was chosen to capture the resuspension of material within the estuary. Power of erosion and erosion coefficient parameters were set to the default value; 8.3 and 5e-05, respectively. The density of the bed layer was set to 350 kg/m^3.

4.2.1.4 Suspended- and Bed-load transport

MIKE 21 MT only simulates the suspended-load component of the sediment transport. The bed-load transport that mainly affect the coarsest particles is not included in the numerical modelling. This limitation is expected to reduce the subsequent long-term transport of sand throughout the estuary once it enters through the new Kaituna River re-diversion and initially deposits within the estuary. However it can be expected there will be some initial deposition in the upper part of the estuary, as the estuary finds a new morphological balance after the significant change to the hydrodynamic regime with the re-diversion, which likely reduces impact of not including bed-load transport.

4.2.1.5 Catchment sediment discharge

Discharge of catchment sediments were set-up at Sites 56, 58 and 59 (shown in Figure 4-4) in the MT model. The MT model is also characterised by an open boundary located at the culvert where the Kaituna River discharges into the Maketū Estuary. The discharge of sediments coming from the Kaituna River has been determined from the catchment model outputs (for all of the Kaituna River) and the predicted portion of total Kaituna River flows entering the Maketū Estuary obtained from the predicted salinities from the 3D HD model.

Table 4-2 provides an overview of the catchment sediment loads for Baseline, Scenario 1 and Scenario 2 .Timeseries of daily discharge for each sediment fraction across the Kaituna River culvert into the Maketū Estuary and the other three catchment sources are presented in Figure 4-11 to Figure 4-14. The discharge of sediments associated with the Kaituna River is largely dominant compared to the three other sources (56,58,59). The morphological changes over the estuary associated with the release of sediments at these other sites is expected to be of relative low importance compared to sediment transport through the new dredged channel.

Table 4-2 Catchment sediment loads for Baseline, Scenario 1 and Scenario 2 over 2014 for the 5 sediment fractions and the 5 canals specified in the mud transport model.

Sources	Mean flow (m^3/s)		
	Baseline	**Scenario 1**	**Scenario 2**
Kaituna River	14.072	14.07175	14.07175
56	0.251	0.221491	0.221491
58	0.315	0.339343	0.339343
59	0.065	0.062364	0.062364
Sources	**Clay (Kg/yr)**		
Kaituna River	176081	47007	215336
56	3845	2661	2940
58	5472	4147	4838
59	1457	922	1339
Sources	**Silt (Kg/yr)**		
Kaituna River	1936896	517083	2368697
56	42302	29277	32349
58	60193	45627	53219
59	16029	10152	14730
Sources	**Very fine sand (Kg/yr)**		
Kaituna River	845191	225636	1033613
56	18459	12775	14115
58	26266	19909	23223
59	6994	4430	6427
Sources	**Fine sand (Kg/yr)**		
Kaituna River	387379	103416	473739
56	8460	5855	6469
58	12038	9125	10643
59	3205	2030	2946
Sources	**Medium sand (Kg/yr)**		
Kaituna River	176081	47007	215336
56	3845	2661	2940
58	5472	4147	4838
59	1457	922	1339
Sources	**Total (Kg/yr)**		
Kaituna River	3521629	940151	4306722
56	76913	53232	58816
58	109442	82958	96763
59	29143	18459	26782
Total	**3737127**	**1094800**	**4489083**

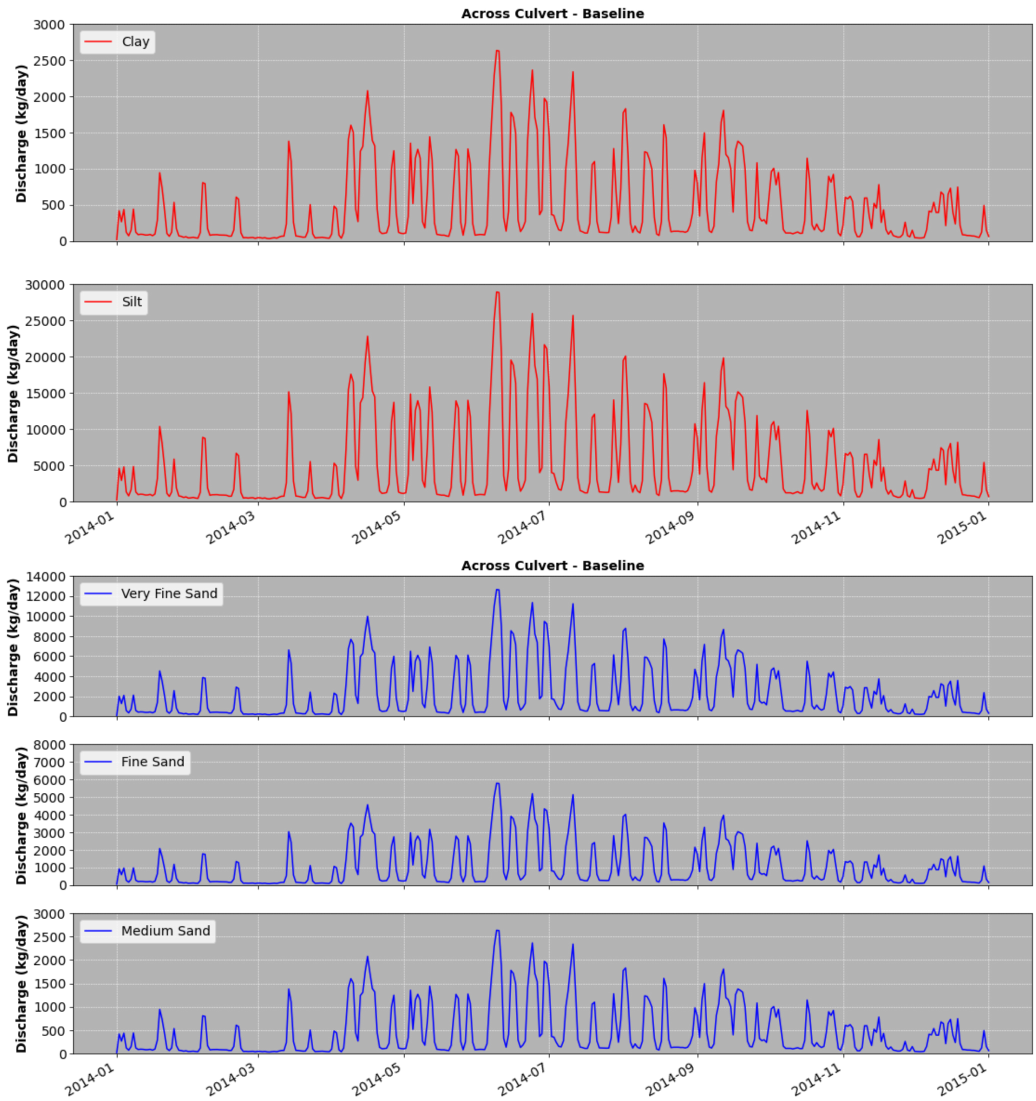

Figure 4-11 Clay, silt, very fine sand, fine sand and medium sand discharge across the Kaituna River culvert located to the west of Maketū Estuary for Baseline over 2014. Red and blue colours represent the mud and sand classes, respectively. Discharges were calculated combining the catchment model outputs with the percentage of mixing determined from the 3D HD model.

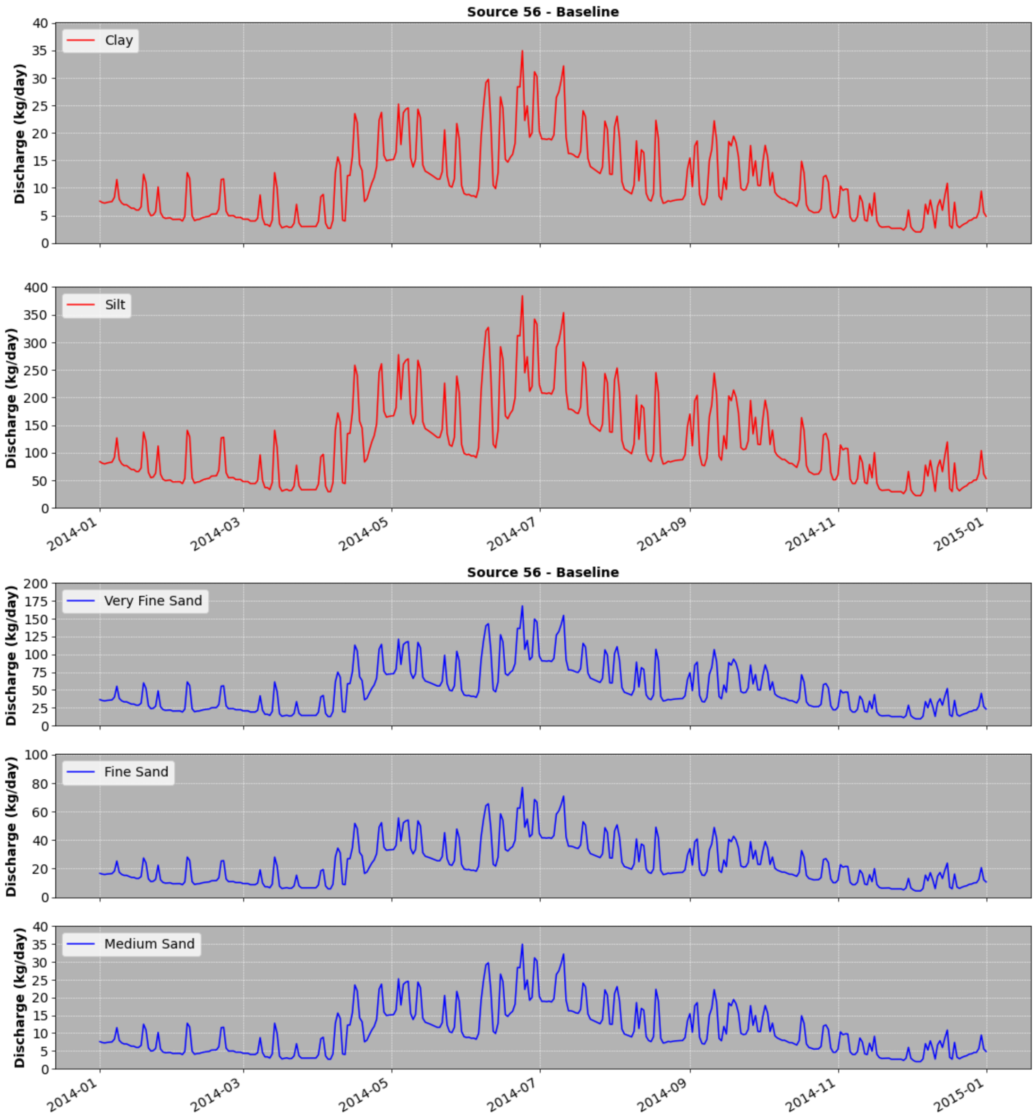

Figure 4-12 Clay, silt, very fine sand, fine sand and medium sand discharge from Source 56 for Baseline over 2014 based on the catchment model outputs. Red and blue colours represent the mud and sand classes, respectively.

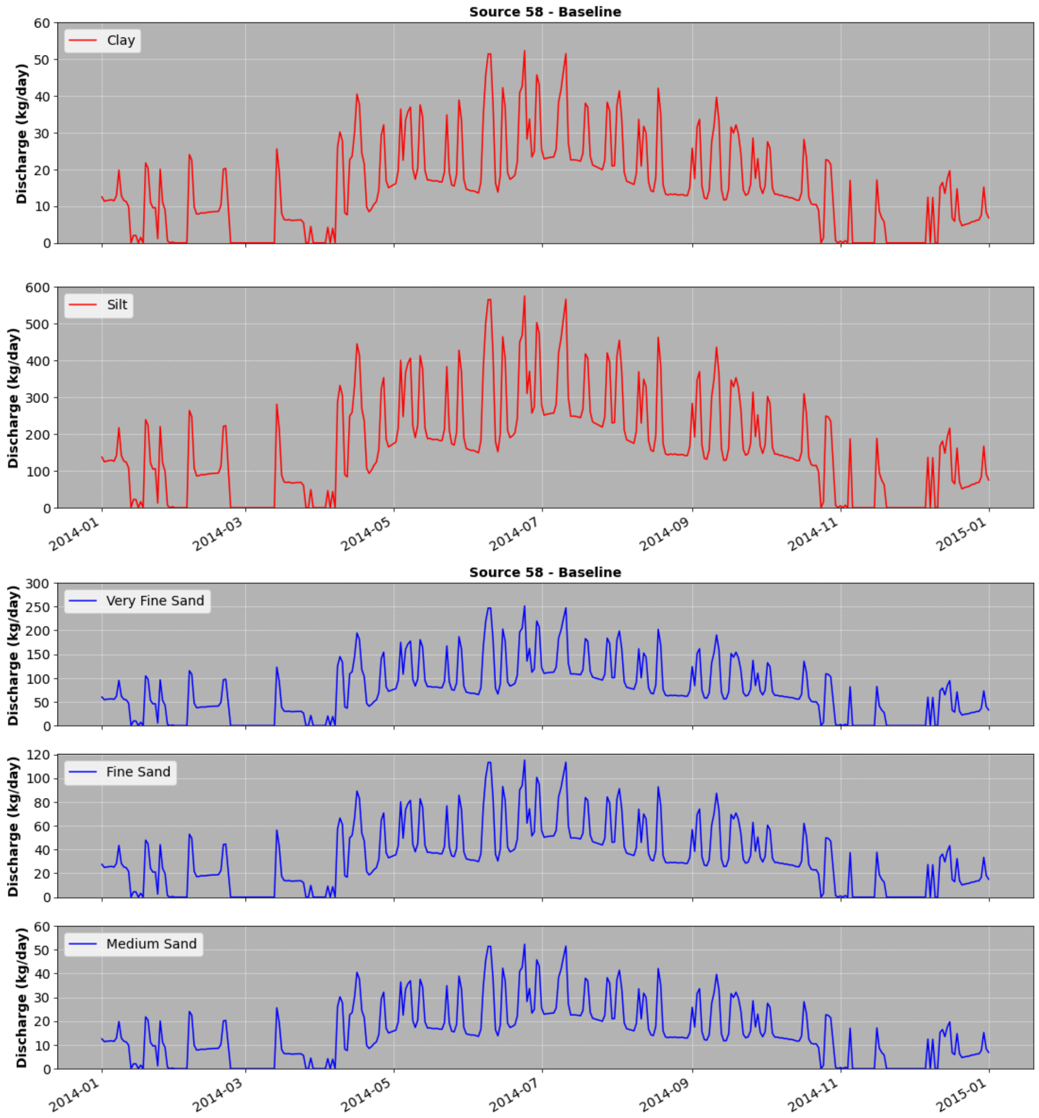

Figure 4-13 Clay, silt, very fine sand, fine sand and medium sand discharge from Source 58 for Baseline over 2014 based on the catchment model outputs. Red and blue colours represent the mud and sand classes, respectively.

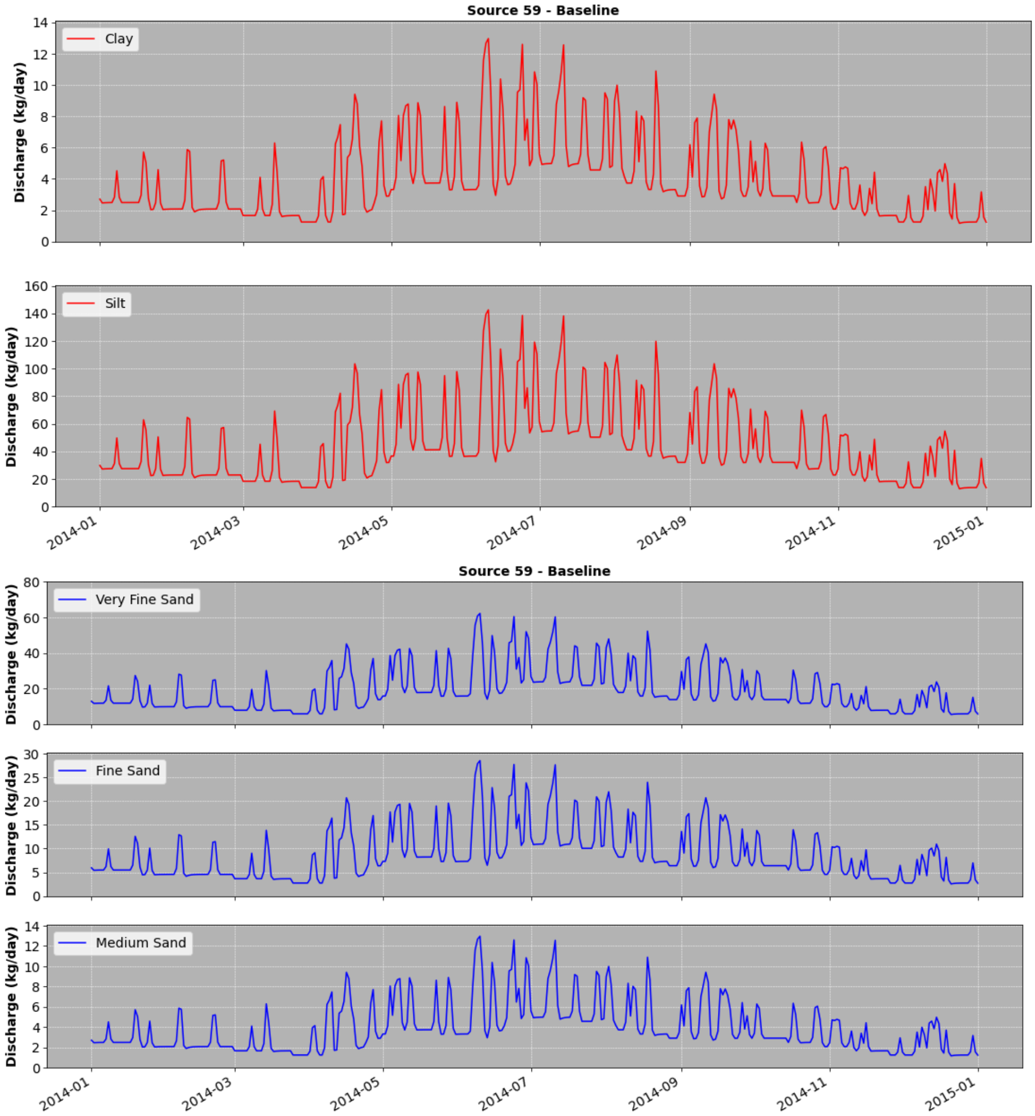

Figure 4-14 Clay, silt, very fine sand, fine sand and medium sand discharge from Source 59 for Baseline over 2014 based on the catchment model outputs. Red and blue colours represent the mud and sand classes, respectively.

4.3 Water Quality Model

4.3.1 Bacteria Assessment

The MIKE 21 Transport module (DHI, 2020e) was used to simulate the transport of E.cocci and F.coli in Maketū Estuary.

The transport module calculates the resulting transport of materials based on the flow conditions from the hydrodynamic module.

To account for the decay of bacteria because of solar radiation, salinity and other processes, a conservative inactivation rate is applied to the tracer in line with recent findings that calculate a first order decay rate constant of E.cocci of below 2 per day under low light conditions (Peter, 2016). Based on previous calibrated and validated studies carried out in New Zealand (Tuckey et al., 2019), a first order decay rate constant of 0.7 per day was used.

4.3.1.1 Model Inputs

The SOURCE model outputs of E.coli were used as inputs to the model.

Since the focus of bacterial assessment is E.cocci and F.coli, the following regression equations (adapted from Scholes 2018) were applied to transform E.coli data set into E.cocci and F.coli data sets respectively –

$$\text{F.coli} = (\text{E.coli} - 1.7896) / 0.8213 \quad (R^2 = 0.95)$$

$$\text{Log (E.cocci)} = \text{Log (F.coli)} / 1.0659 \quad (R^2 = 0.85)$$

SOURCE model outputs for the Baseline Scenario, Scenario 1 (Scenario – Natural), and Scenario 2 (Scenario C+M1) were used as catchment loads flowing into Maketū Estuary.

No other loads (either atmospheric deposition or oceanic input) were considered as additional bacterial loads into Maketū Estuary.

For the Baseline scenario, catchment loads of E.cocci and F.coli into Maketū Estuary amounted to 7.74×10^{14} cfu/yr, and 1.1×10^{15} MPN/yr respectively.

In Scenario 1, the loads are 4.8×10^{14} cfu/yr of E.cocci and 6.6×10^{14} MPN/yr of F.coli.

In Scenario 2, the loads are 6.7×10^{14} cfu/yr of E.cocci and 9.4×10^{14} MPN/yr of F.coli.

Figure 4-15 and Figure 4-16 show the time series plots of E.cocci and F.coli daily loads into Maketū Estuary respectively.

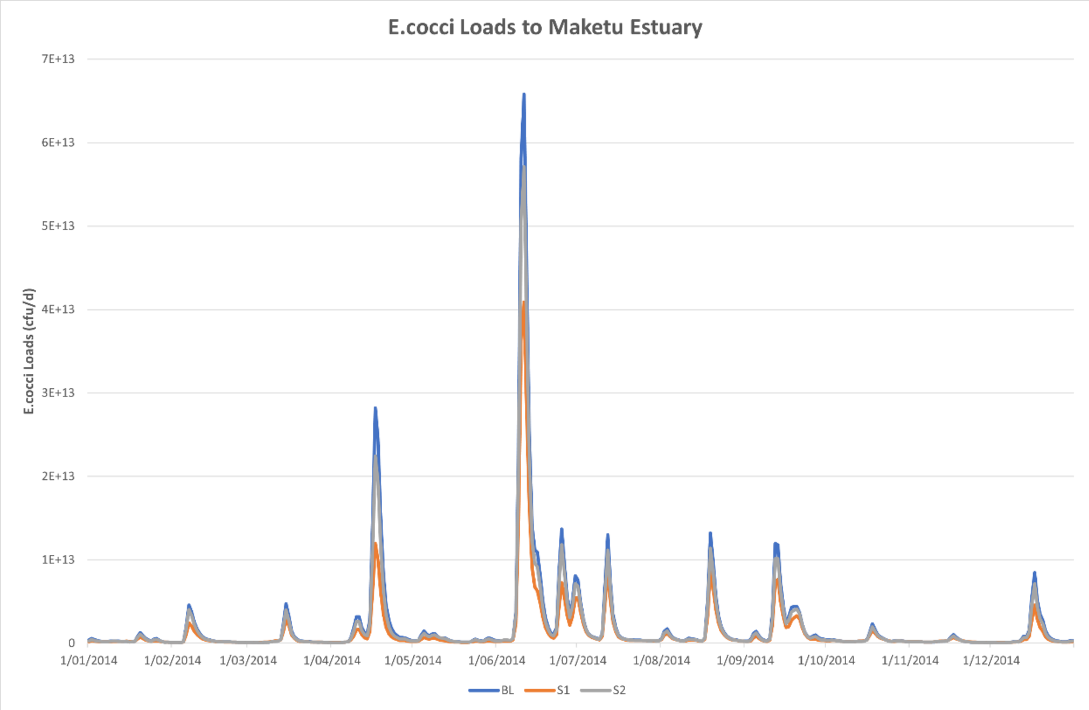

Figure 4-15 Catchment loads (E.cocci) to Maketū Estuary. BL corresponds to Baseline, S1 corresponds to Scenario 1, and S2 corresponds to Scenario 2.

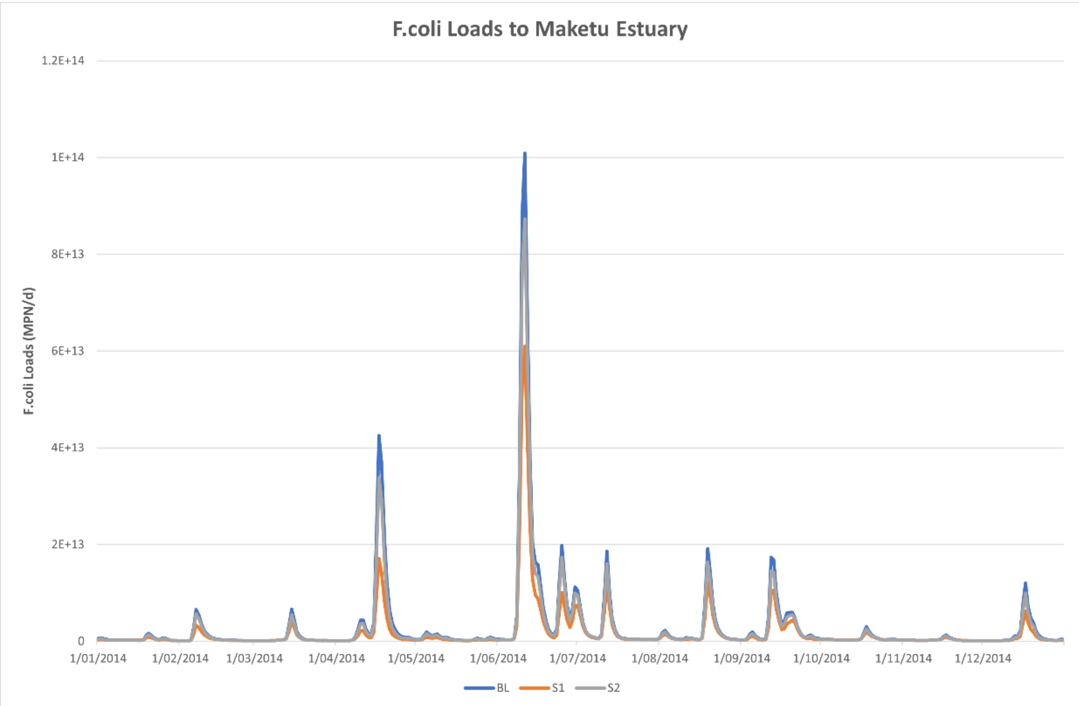

Figure 4-16 Catchment loads (F.coli) to Maketū Estuary. BL corresponds to Baseline, S1 corresponds to Scenario 1, and S2 corresponds to Scenario 2.

In the time series plots, we observe that the inflow loads to Maketū Estuary show two distinct significant peaks of incoming loads in mid-April and mid-June.

The mid-April event contributed 10.6%, 7.2%, and 9.7% of the annual E.cocci load contribution to Maketū Estuary in Baseline, Scenario 1, and Scenario 2 simulations respectively.

The mid-June event contributed 25.1%, 25.5%, and 25.4% of the annual E.cocci load contribution to Maketū Estuary in Baseline, Scenario 1, and Scenario 2 simulations respectively.

The mid-April event contributed 11.1%, 7.4%, and 10.3% of the annual F.coli load contribution to Maketū Estuary in Baseline, Scenario 1, and Scenario 2 simulations respectively.

The mid-June event contributed 26.8%, 27.6%, and 27.3% of the annual F.coli load contribution to Maketū Estuary in Baseline, Scenario 1, and Scenario 2 simulations respectively.

Figure 4-17 and Figure 4-18 show contribution of E.cocci and F.coli loads from the individual sources into Maketū Estuary respectively.

The Kaituna River across contributes between 90% to 96% of the annual loads of E.cocci and F.Coli to Maketū Estuary.

For both the mid-April and mid-June events, and for both E.cocci and F.coli loads, the Kaituna River was the dominant source of loads.

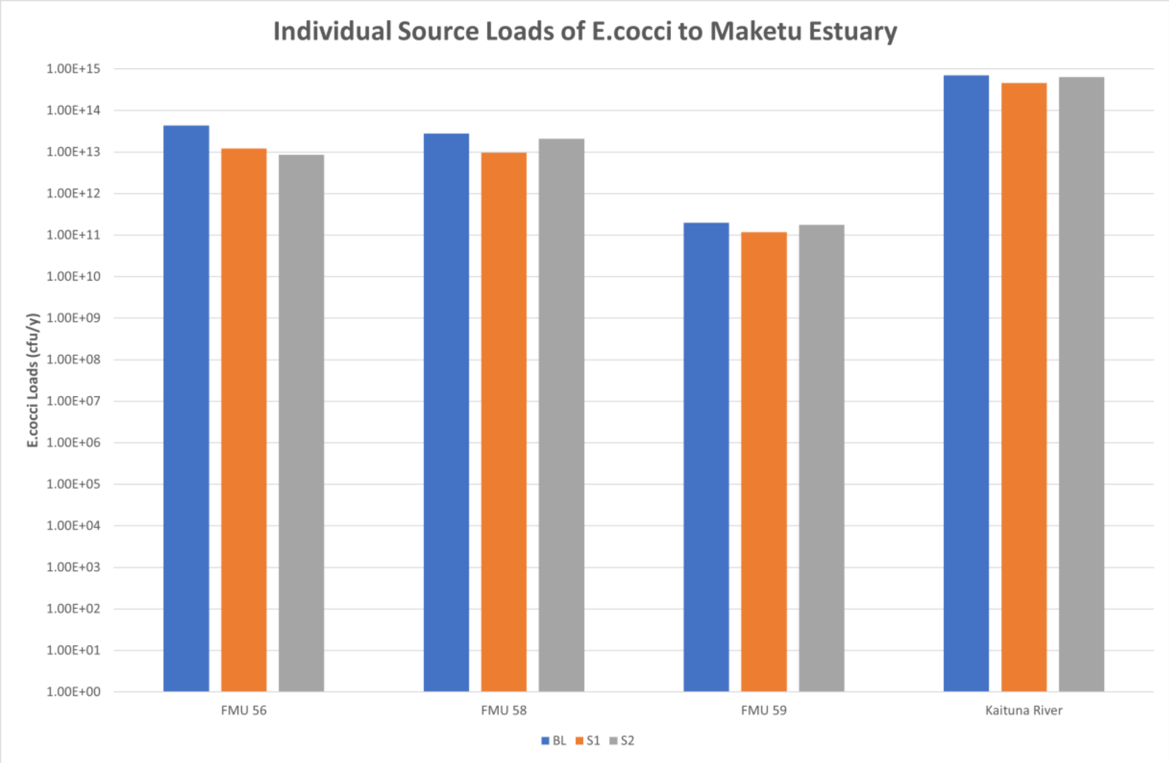

Figure 4-17 Individual source loads (E.cocci) to Maketū Estuary. BL corresponds to Baseline, S1 corresponds to Scenario 1, and S2 corresponds to Scenario 2. Y-axis is in log scale.

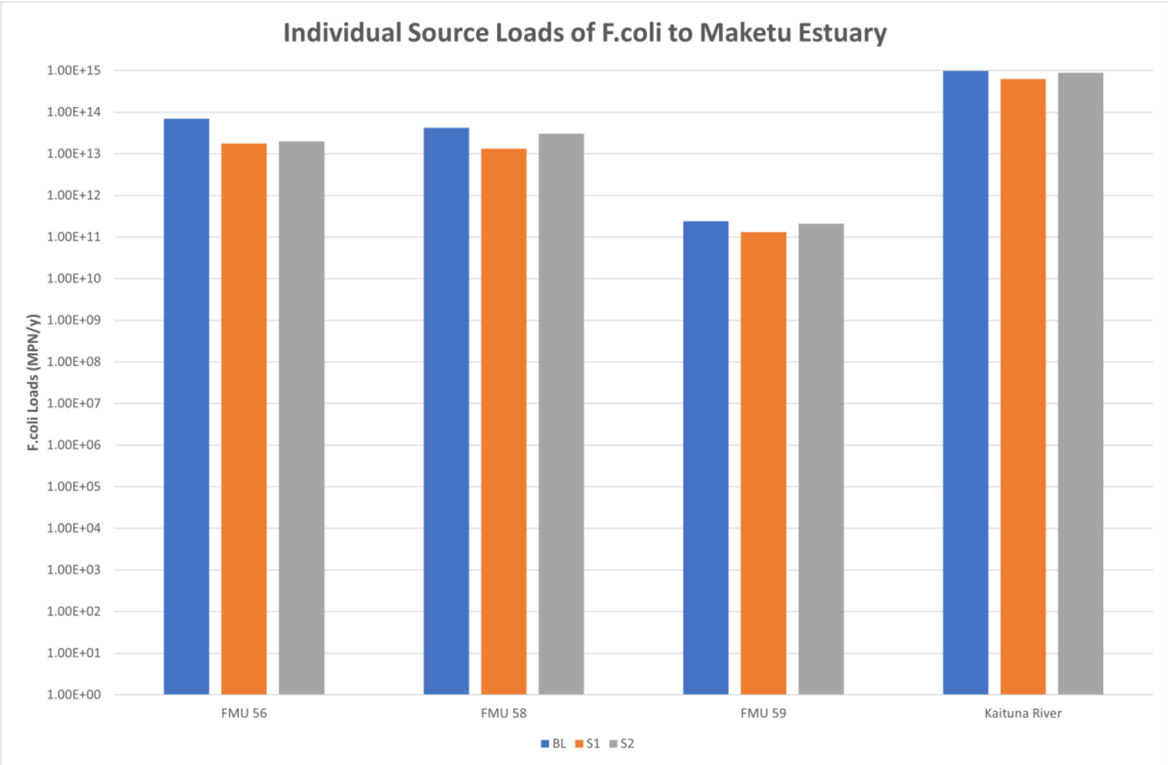

Figure 4-18 Individual source loads (F.coli) to Maketū Estuary. BL corresponds to Baseline, S1 corresponds to Scenario 1, and S2 corresponds to Scenario 2. Y-axis is in log scale.

Analysis of the E.cocci inflows with respect to meeting microbiological water quality guidelines for primary contact recreation/bathing was carried out.

Guidelines indicate that the concentration of E.cocci must not exceed 280 cfu/100ml (Scholes, 2018).

Results (see Figure 4-19) showed that Source 59 inflows met the guideline value 100% of the annual period in all three simulations.

The Kaituna River inflows met the guideline value for more than 95% of the annual period in all three simulations.

Seasonal investigation of guideline exceedances for E.cocci loads to Maketū Estuary under the Baseline scenario showed that, on average, the guideline was exceeded for 18% of Winter[8]. In contrast, the guideline was exceeded for about 10% of Spring[9], 17% of Summer[10], and 15% of Autumn[11].

For Scenario 1, the guideline was exceeded for about 9% of Winter, 2% of Spring, 6% of Summer, and 8% of Autumn.

For Scenario 2, the guideline was exceeded for about 12% of Winter, 4% of Spring, 9% of Summer, and 11% of Autumn.

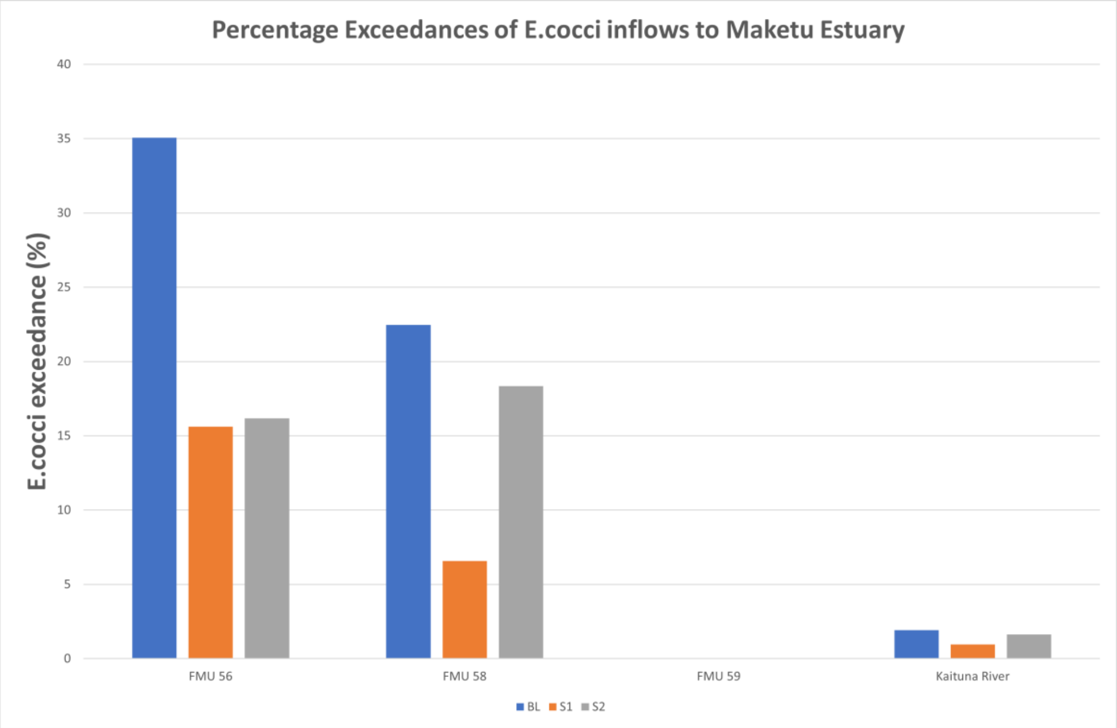

Figure 4-19 Percentage of time guideline exceeded for loads (E.cocci) to Maketū Estuary in 2014. BL corresponds to Baseline, S1 corresponds to Scenario 1, and S2 corresponds to Scenario 2.

[8] Defined as 1^{st} June to 31^{st} August.

[9] Defined as 1^{st} September to 30^{th} November.

[10] Defined as 1^{st} December to 28^{th} February.

[11] Defined as 1^{st} March to 31^{st} May.

Analysis of the 2014 inflows with respect to meeting microbiological water quality guidelines for shellfish gathering was also carried out.

The guidelines indicate that median faecal coliform content of water samples taken over a shellfish-gathering season shall not exceed a Most Probable Number (MPN) of 14/100 mL, and not more than 10% of samples should exceed an MPN of 43/100 mL (Scholes, 2018).

Results (Figure 4-20) showed that Source 59 inflows met the guideline value for more than 98% of the annual period in all three simulations.

Kaituna River inflows met the guideline value for more than 95% of the annual period in all three simulations.

Seasonal investigation of guideline exceedances above MPN of 43/100 mL for F.coli loads to Maketū Estuary showed that, on average, the guideline was exceeded for 60% of Winter under the Baseline Scenario. In contrast, the guideline was exceeded for 46% of Spring, 47% of Summer, and 45% of Autumn.

For Scenario 1, the guideline was exceeded for about 49% of Winter, 33% of Spring, 38% of Summer, and 37% of Autumn.

For Scenario 2, the guideline was exceeded for about 55% of Winter, 38% of Spring, 42% of Summer, and 41% of Autumn.

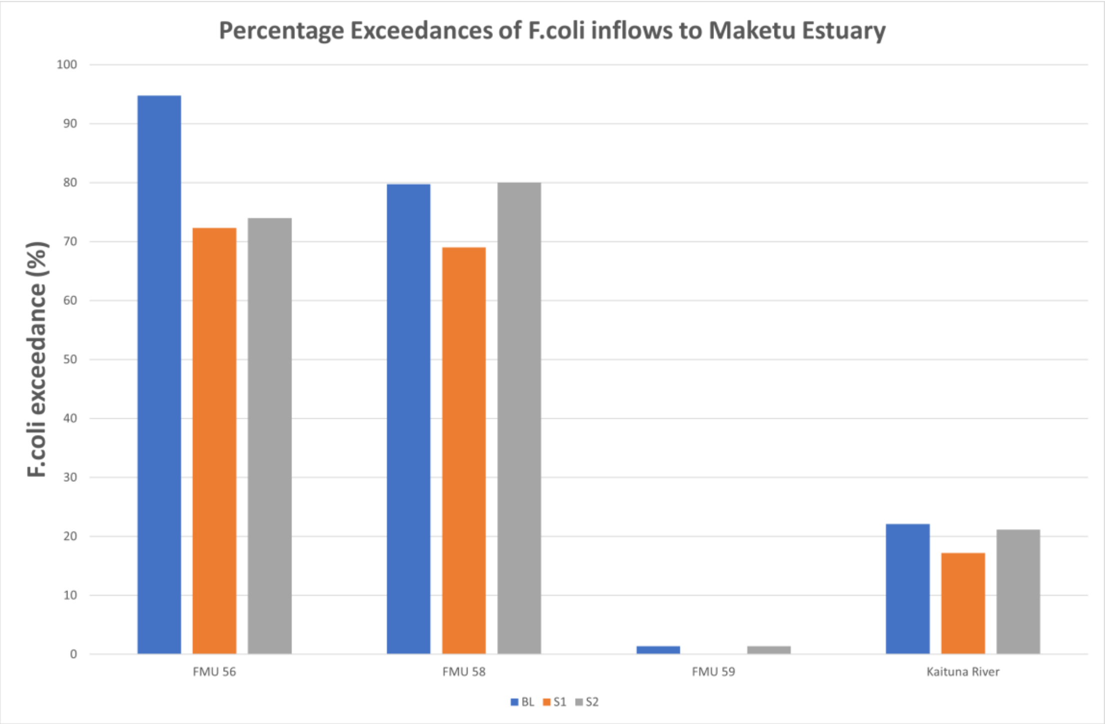

Figure 4-20 Percentage of time guideline exceeded for loads (F.coli) to Maketū Estuary in 2014. BL corresponds to Baseline, S1 corresponds to Scenario 1, and S2 corresponds to Scenario 2.

4.3.2 Nutrient and Ecological Assessment

MIKE ECO Lab module (DHI, 2020f) was used to simulate the nutrient and ecological processes in Maketū Estuary. MIKE ECO Lab implements in the flow and transport model the formulation of the biological, chemical, sediment, and settling processes important for environmental analysis of water bodies. MIKE ECO Lab is an equation solver using predefined reaction kinetic models (MIKE ECO Lab templates) and for user formulated models.

MIKE ECO Lab provides a generic water quality model framework describing the governing processes of ecosystems and their interactions with water quality components such as dissolved oxygen, organic matter, nutrients, heavy metals and eutrophication.

MIKE ECO lab can be run either fully coupled or decoupled mode with hydrodynamics. For this work it is run in decoupled mode so that the forcings were all derived from pre run MIKE 21 HD outputs. That is, the hydrodynamic model was firstly run for 2014 and the ecological model was run thereafter (forced by result files from the hydrodynamic model). This allows significant gain in the overall efficiency of the model workflow.

4.3.2.1 Model Setup

The MIKE ECO Lab model template used for this work contains 98 state variables, 308 constants, 29 forcing functions, 285 auxiliary processes and 476 processes.

In combination, this provides the simulation of the independent cycles of Carbon (C), Nitrogen (N) and Phosphorous (P) as shown in Figure 4-21.

The photo-autotrophic growth processes are light and temperature controlled two-step nutrient utilization with a variable C:N:P stoichiometry.

The model C, N and P cycles follow commonly accepted cycles in the water column and sediment (Canfield 2005).

The ecological model also includes a sediment transport component which includes sediment pools of inorganic matter, and organic C, N and P. These pools of nutrients can be resuspended from the seabed during periods of stronger predicted currents.

The above ground biomass of seagrass (Z. muelleri) is represented in the model with three state variables carbon (g C m^{-2}), nitrogen (g N m^{-2}), and phosphorus (g P m^{-2}).

Besides seagrass, microbenthic algae and opportunistic macroalgae are included as state variables in the model, as shown in Figure 4-22. Their abundance is controlled by growth and loss processes that are influenced by nutrient availability, benthic light intensity and temperature. The model includes current generated resuspension of suspended solids, which can be increased due to movements of ephemeral macroalgae sourcing over the sediment (Canal-Vergéset 2014) or decreased by microbenthic algae. Seagrass biomass is described as a balance between production and loss, which can be divided into general losses and stress related losses. General losses are respiration under normal light conditions, loss due to seed release and natural death. Elevated biomasses of ephemeral macroalgae generate additional stress by increasing the resuspension and thereby reducing the light condition for seagrass growth.

Initial conditions were generated by pre running the models with default starting values for several years until a steady state was achieved. Results from these spin-up simulations were then used as initial conditions for the Scenario simulations. Boundary conditions for the state variables were defined based on measurements reported in Park (2005).

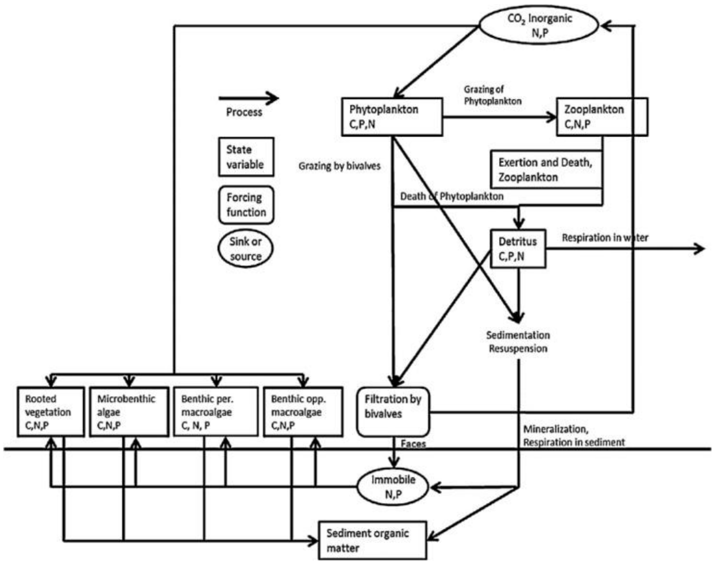

Figure 4-21 Main state variable processes in the MIKE ECO lab ecological model.

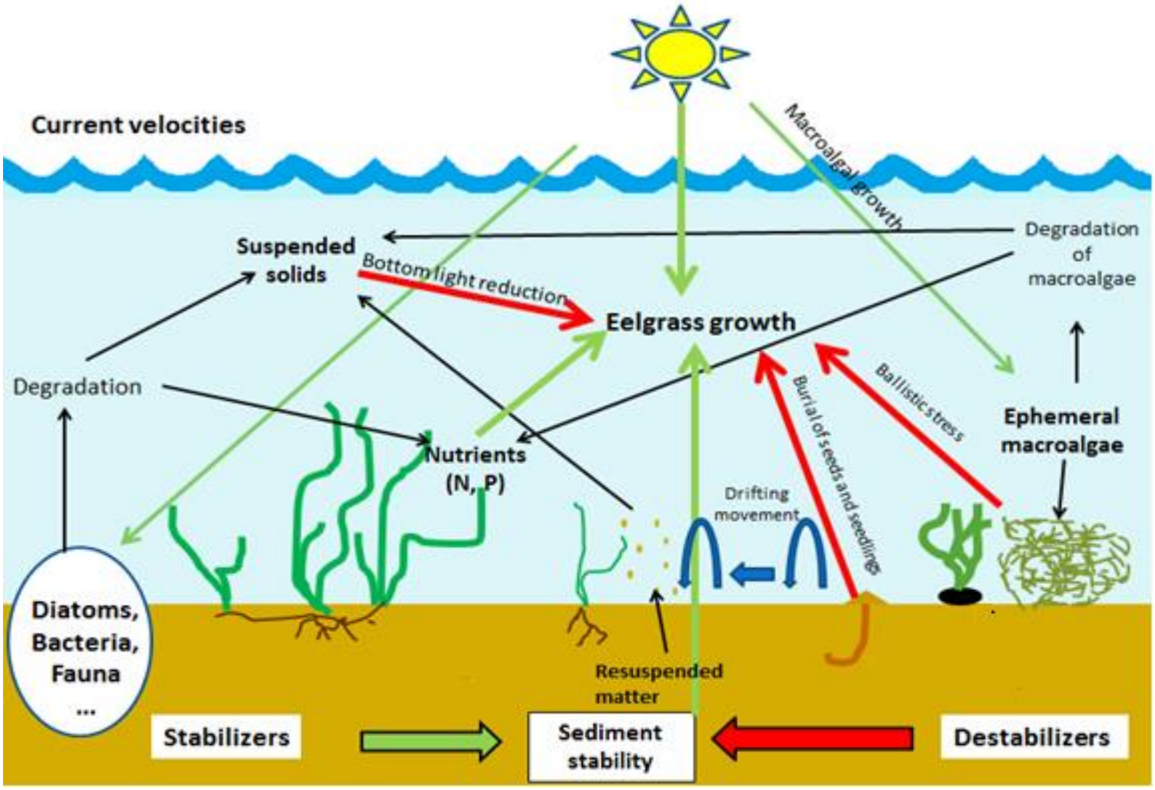

Figure 4-22 Seagrass and Macroalgae modelling processes.

4.3.2.2 Model Inputs

SOURCE model outputs of Total Nitrogen (TN) and Total Phosphorous (TP) were used as inputs to the ecological model. These inputs were fractionated to different parameters, including NH_4 (Ammonium), NOx (Nitrite-Nitrate), PO_4 (Phosphate), DN (Detritus Nitrogen), DP (Detritus Phosphorous), DC (Detritus Carbon), CDOC (Coloured Refractory Dissolved Organic Carbon), CDON (Coloured Refractory Dissolved Organic Nitrogen), CDOP (Coloured Refractory Dissolved Organic Phosphorous), LDOC (Labile Dissolved Organic Carbon), LDON (Labile Dissolved Organic Nitrogen), and LDOP (Labile Dissolved Organic Phosphorous). The fractions derived for Waihī Estuary modelling were used for Maketū Estuary modelling.

For the Baseline scenario, Total Nitrogen and Total Phosphorous inflows from the four sources into Maketū Estuary amounted to 1140 tonnes/year and 49.1 tonnes/year respectively.

In Scenario 1, 366 tonnes/year of TN loads and 24.2 tonnes/year of TP loads into Maketū Estuary were observed.

In Scenario 2, 699 tonnes/year of TN loads and 41.5 tonnes/year of TP loads into Maketū Estuary were observed.

Figure 4-23 and Figure 4-24 show the time series plots of TN and TP loads into Maketū Estuary respectively. Loads were converted to a load per unit area (mg/m^2/d) by assuming a mean High Tide Area of Maketū Estuary of 245 ha.

Interim guidelines of 200 mg/m^2/d for TN and 14.74 mg/m^2/d for TP (Park 2018) are also highlighted in the two figures.

Loads to Maketū Estuary exceed the interim guideline of 200 mg/m^2/d of TN for 99.5%, 42.5%, and 86% of 2014 for the Baseline, Scenario 1, and Scenario 2 runs respectively.

For TP, loads to Maketū Estuary exceed the interim guideline of 14.74 mg/m^2/d for 88.8%, 79.2%, and 83.4% of 2014 for the Baseline, Scenario 1, and Scenario 2 runs respectively.

Figure 4-23 shows one distinct peak of TN load in mid-June whereas Figure 4-24 shows two distinct peaks of TP loads in mid-April and mid-June respectively.

In Figure 4-23, the mid-June event contributed 9.6%, 19.9%, and 13.1% of the TN load contribution to Maketū Estuary in Baseline, Scenario 1, and Scenario 2 simulations respectively.

In Figure 4-24, the mid-April event contributed 5.8%, 2.3%, and 4.8% of the annual TP load contribution to Maketū Estuary in Baseline, Scenario 1, and Scenario 2 simulations respectively.

In Figure 4-24, the mid-June event contributed 10.1%, 5.3%, and 9.1% of the annual TP load contribution to Maketū Estuary in Baseline, Scenario 1, and Scenario 2 simulations respectively.

For both mid-April and mid-June events, the Kaituna River was the dominant source of contribution to both TN and TP loads to Maketū Estuary.

Figure 4-25 and Figure 4-26 show contribution of TN and TP loads from the individual sources into Maketū Estuary respectively.

The Kaituna River contributes between 91% and 99% of the annual TN loads, and 94% to 96% of the annual TP loads to Maketū Estuary in the three simulation runs.

Seasonal investigation of TN loads to Maketū Estuary showed that Winter loads ranged from 46-54% of the total annual load in all three scenario runs. In contrast, the Summer loads ranged from 11-13% of the total annual load, Spring loads ranged from 19-21% of the total annual load, and Autumn loads ranged from 16-20% of the total annual loads in all three scenario runs.

TN loads from the Kaituna River formed about 99% of the total loads in each of the four seasons for Scenario 1 run, and about 90-92% of the total loads in each of the four seasons for Baseline and Scenario 2 runs respectively.

Seasonal investigation of TP loads to Maketū Estuary showed that Winter loads ranged from 37-42% of the total annual load. In contrast, Summer loads ranged from 16-18% of the total annual load, Spring loads ranged from 19-21% of the total annual load, and Autumn loads ranged from 16-20% of the total annual loads in all three scenario runs.

Total Phosphorous loads from the Kaituna River formed about 96% of the total loads in each of the four seasons for Scenario1 run, about 92-96% of the total loads in each of the four seasons for Baseline run, and about 95-97% of the total loads in each of the four seasons for Scenario 2 run respectively.

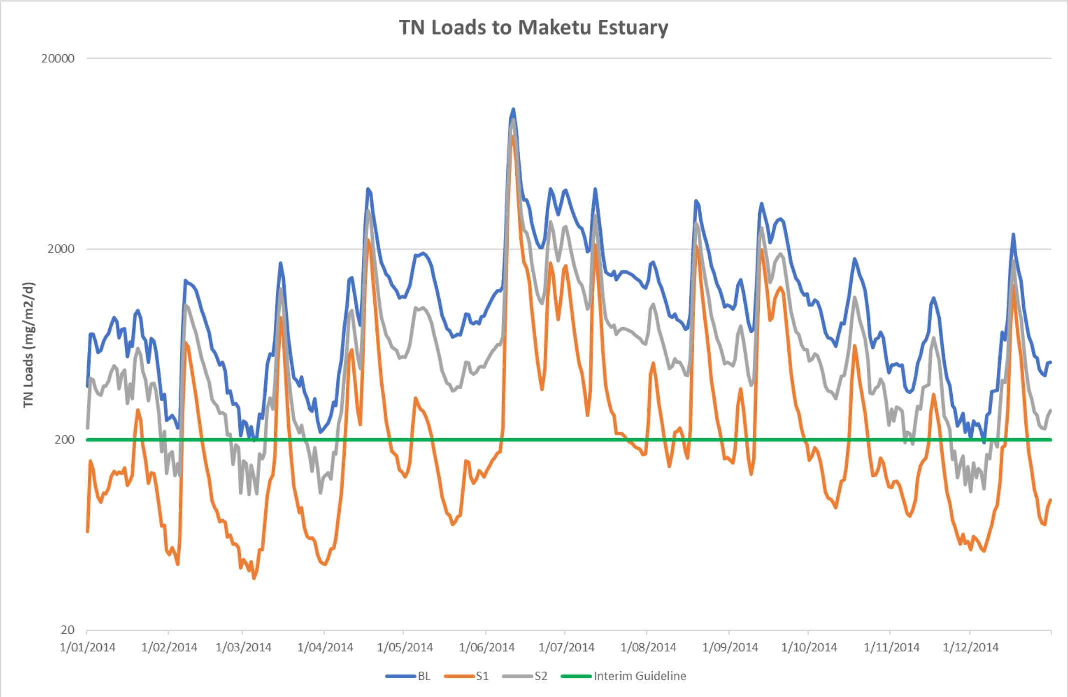

Figure 4-23 Catchment Loads (Total Nitrogen) to Maketū Estuary. BL corresponds to Baseline, S1 corresponds to Scenario 1, and S2 corresponds to Scenario 2. Y-axis is in log scale.

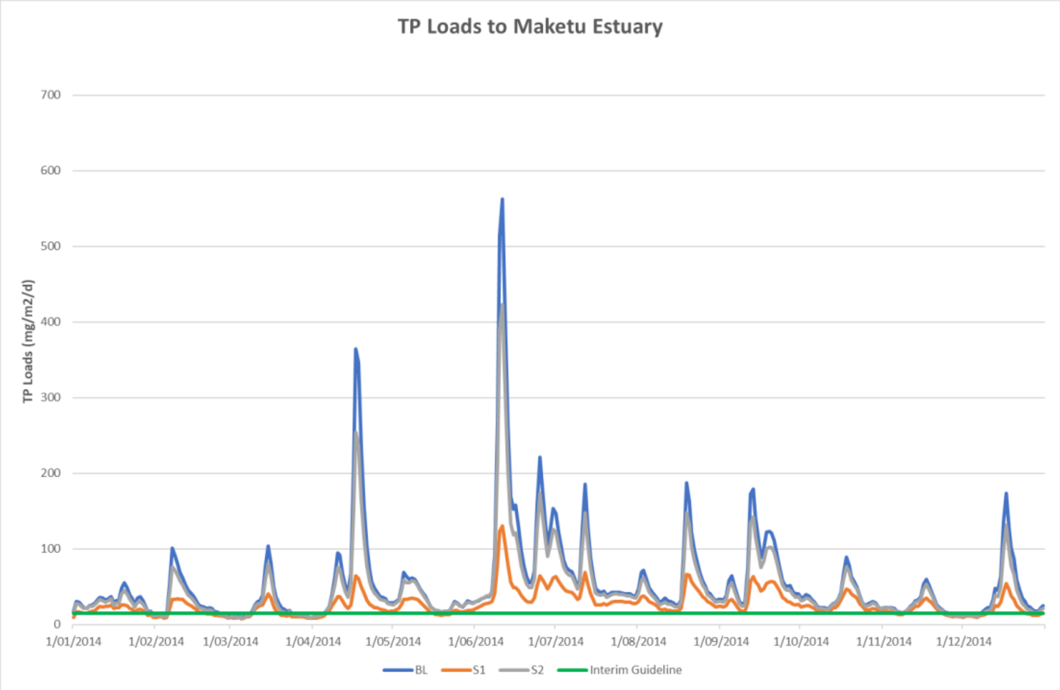

Figure 4-24 Catchment Loads (Total Phosphorous) to Maketū Estuary. BL corresponds to Baseline, S1 corresponds to Scenario 1, and S2 corresponds to Scenario 2.

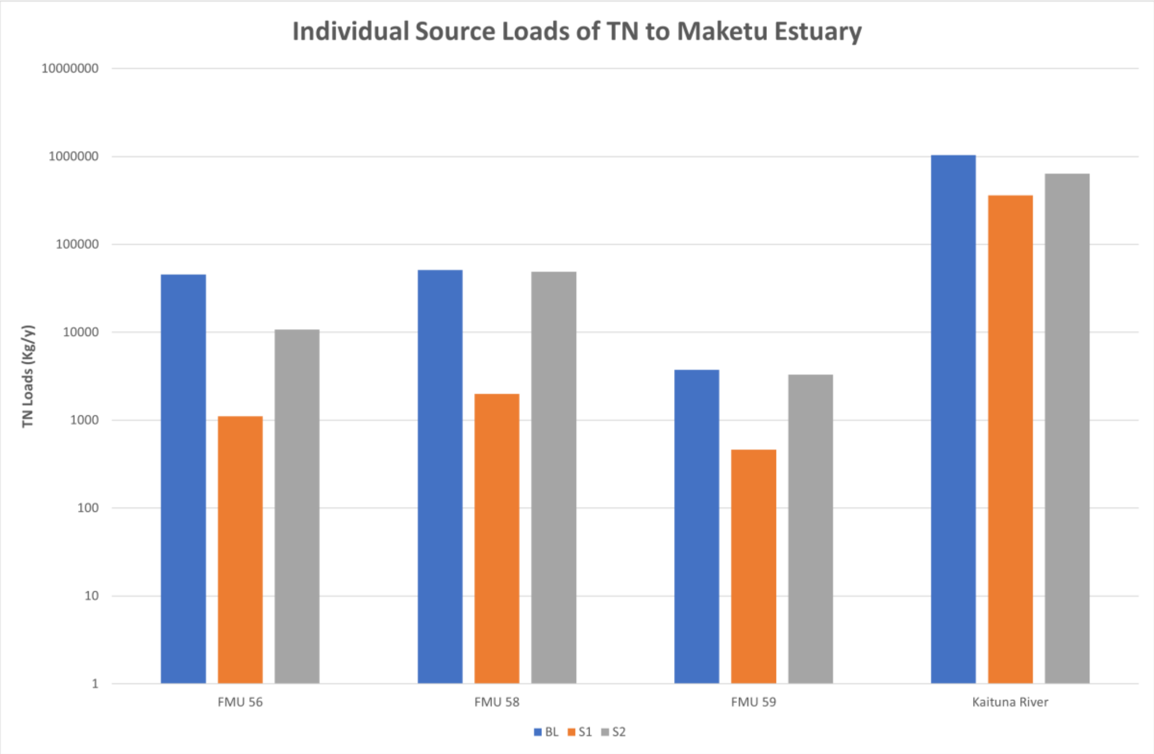

Figure 4-25 Individual source loads (Total Nitrogen) to Maketū Estuary. BL corresponds to Baseline, S1 corresponds to Scenario 1, and S2 corresponds to Scenario 2. Y-axis is in log scale.

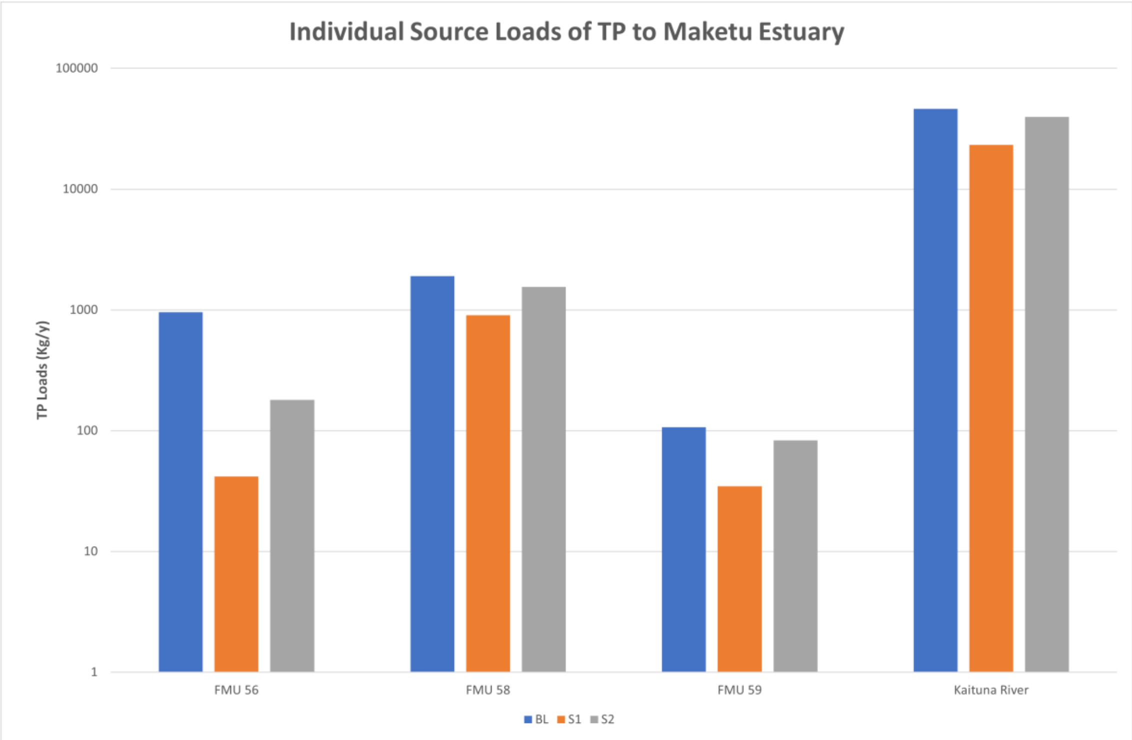

Figure 4-26 Individual source loads (Total Phosphorous) to Maketū Estuary. BL corresponds to Baseline, S1 corresponds to Scenario 1, and S2 corresponds to Scenario 2. Y-axis is in log scale.

5 Results

5.1 Sediment Transport Results

Care has to be taken when interpreting the results from sediment modelling.

The recent Kaituna River re-diversion significantly modifies the hydrodynamics within the estuary, with an increase in water from the Kaituna River and a corresponding reduction in water through the estuary mouth. The Maketū Estuary will respond morphologically to the change in the hydrodynamic regime, with some areas, especially the flood delta expected to erode (or at least not continue to expand) in the coming years (DHI, 2014) and some minor infilling in other areas.

The sedimentation patterns predicted with the current modelling are representative of the estuary with the current bathymetry, however it can be expected the sedimentation behaviour will change over longer-time frames (~10 years), as the estuary responds morphologically to the new hydrodynamic regime. The modelling indicates some infilling with catchment derived sediment in the upper estuary which, over time, may reduce as the estuary finds its new morphologically balance.

The peak ebb and flood neap and spring tidal currents and associated bed shear stress are presented in Figure 5-1 through to Figure 5-4.

A classification of critical bed shear stress for erosion of different sediment particles sizes is shown in Table 5-1, derived from U.S. Department of the Interior, 2008). The spatial exceedance probability of each critical shear stress for resuspension for each sediment fraction, is presented in Figure 5-5 to 5-9. These plots show the percentage of time that the particular bed shear stress is exceeded over the period of the model simulation.

Table 5-1 Critical bed shear stress for erosion per grain-size classification (from U.S. Department of the Interior, 2008)

Particle Classification	Ranges of particle diameters (mm)	Critical Bed Shear Stress (N/m^2)
Coarse cobble	128 – 256	112 – 223
Fine cobble	64 – 128	53.8 – 112
Very coarse gravel	32 – 64	25.9 – 53.8
Coarse gravel	16 – 32	12.2 – 25.9
Medium gravel	8 – 16	5.7 – 12.2
Fine gravel	4 – 8	2.7 – 5.7
Very fine gravel	2 – 4	1.3 – 2.7
Very coarse sand	1 – 2	0.47 – 1.3
Coarse sand	0.5 – 1	0.27 – 0.47
Medium sand	0.25 – 0.5	0.194 – 0.27
Fine sand	0.125 – 0.25	0.145 – 0.194
Very fine sand	0.0625 – 0.125	0.110 – 0.145
Coarse silt	0.0310 – 0.0625	0.0826 – 0.110
Medium silt	0.0156 – 0.0310	0.0630 – 0.0826
Fine silt	0.0078 – 0.0156	0.0378 – 0.0630

The mud fraction percentage obtained by sediment samplings within the estuary is shown in Figure 5-10. Maps of annual bed mass deposition for the clay, silt, very fine sand, fine sand and medium sand fractions obtained from the mud transport model for each scenario are shown in Figures 5-11 to 5-15. Where the finer sediment is predicted to deposit generally matches where there is a higher mud fraction seen in sediment samples. The thickness of the deposited material at the end of the 2014 simulation is shown in Figure 5-16.

The constriction at the estuary entrance generates peak ebb and flood tidal current speeds that exceed 0.8 m/s and propagate through the channel westward up to a shallow section located approximately 2 km from the entrance along the southern margin of the estuary where speeds decrease to less than 0.1 m/s. Over this area, the bed shear stress ranges from 0.01 to 0.1 N/m^2 and the exceedance probability for a threshold of 0.038 $N.m^{-2}$ is less than 30%. This means that marine sediments transported during energetic wave events during a flood tide may penetrate up to 2 km inside the estuary. This is why the observed muddiness are lower than 5% in this section of the main channel.

In the upper part of the estuary to the west, the hydrodynamics in Fords Cut channel is mainly driven by the flow from the Kaituna River and the fact flow is only possible from river to estuary, when river levels are greater in the river compared with the estuary.

When the culverts are open, current speeds exceed 0.6 m/s inducing very high bed shear stresses into the channel. Once the re-diversion channel opens up into the upper part of the estuary, current speeds are reduced significantly (to less than 0.05 m/s). The resultant low bed shear stress fields over the adjacent inter-tidal areas will cause the deposition of sediments in the upper to central region of the Maketū Estuary.

The finer sediments will migrate further into the central inter-tidal area of the estuary, compared with coarser sediments. It is predicted that a short-term sedimentation rate of 1 to 10 cm will of occur over the upper estuary intertidal flats.

Near the culverts, a very quick and short-term morphological response to the expanding of Fords Cut channel is expected to occur in the corner of the channel where the presence of eddies and very low current fields may induce sedimentation. This short-term sedimentation processes should not affect the circulation through the channel over time.

The sediments released into the system by the inner freshwater sources (56,58 and 59) are expected to deposit close to the source and will then be spread over time by bed-load transport (not included in the model). Resuspension may occasionally occur during large floods events. It is important to note that the sediment loads released into the system by these streams are very small compared to those coming from the Kaituna River (Table 4-2).

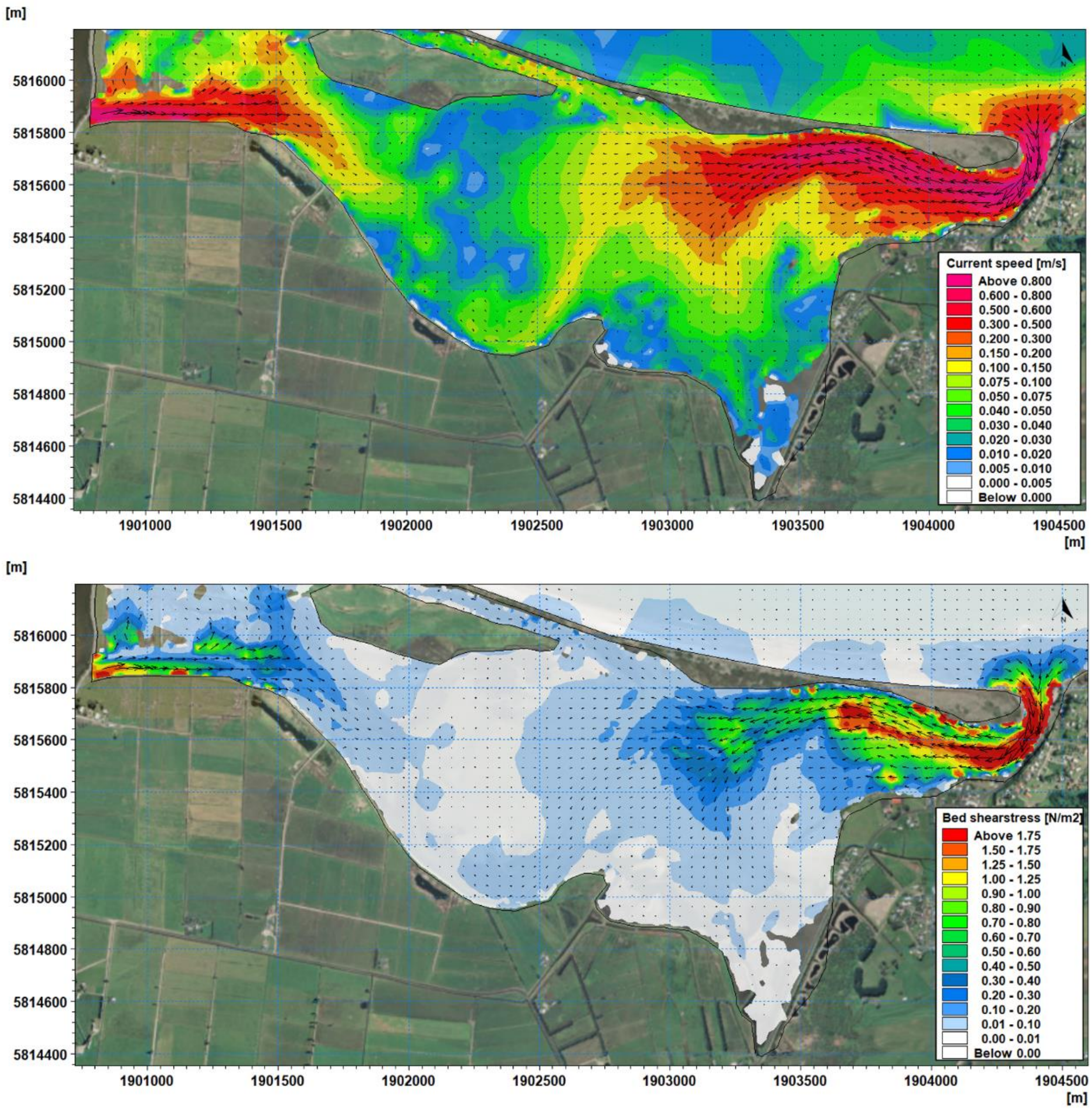

Figure 5-1 Spatial peak flood flow at spring tide (01/02/2014 20:00) and corresponding bed shear stress field.

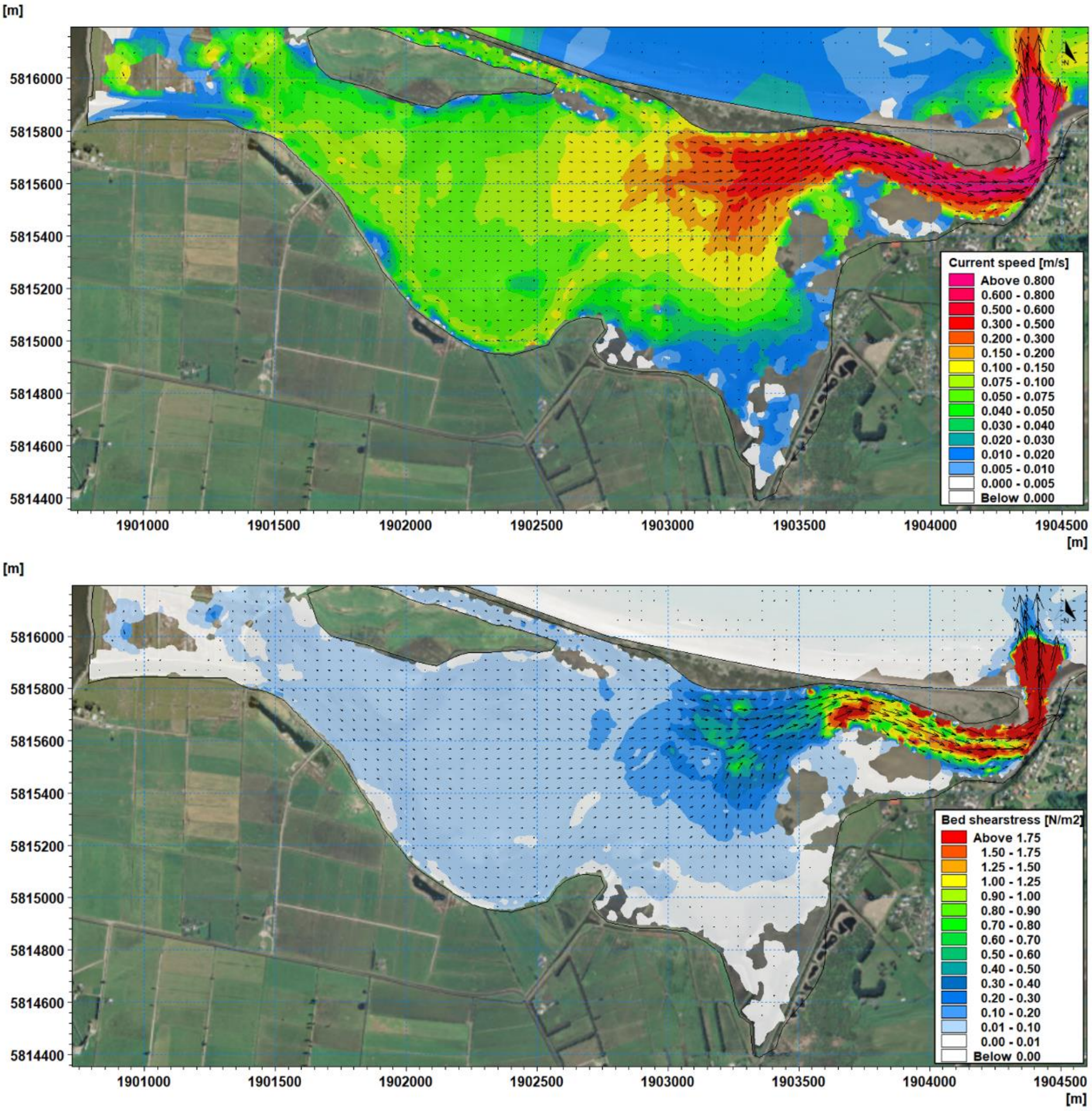

Figure 5-2 Spatial peak ebb flow at spring tide (01/02/2014 20:00) and corresponding bed shear stress field.

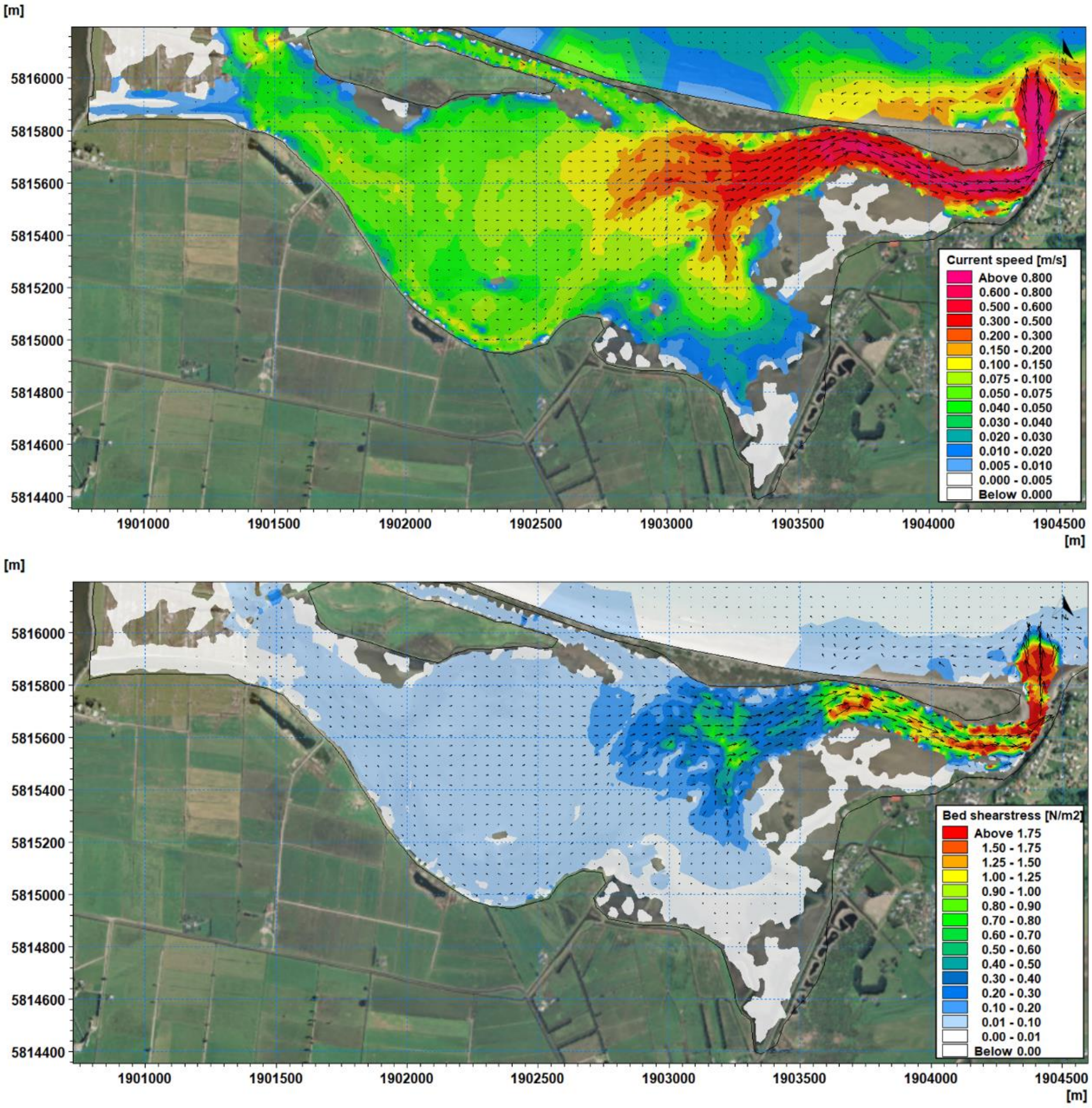

Figure 5-3 Spatial peak ebb flow at neap tide (11/02/2014 21:00) and corresponding bed shear stress field.

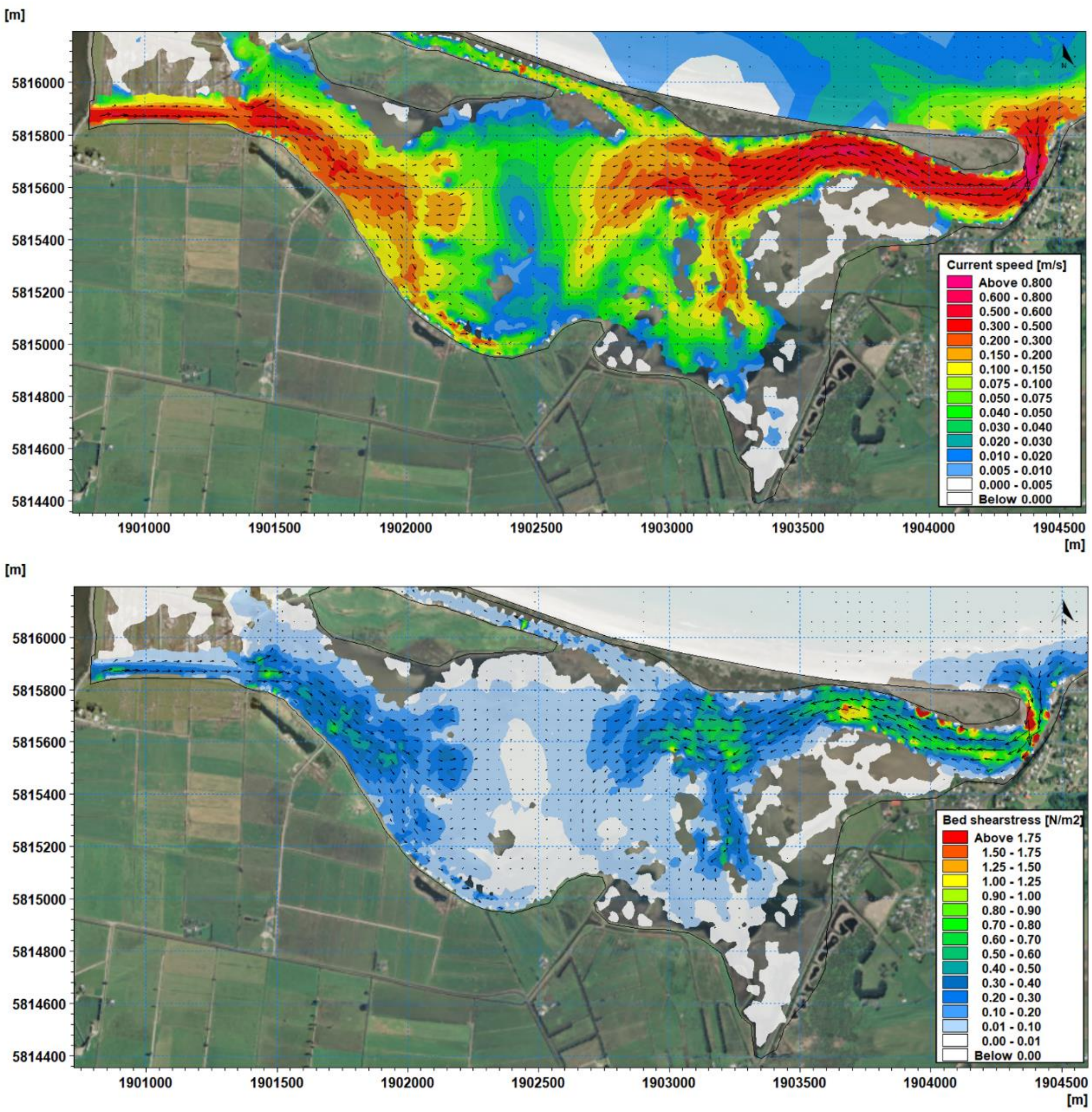

Figure 5-4 Spatial peak flood flow at neap tide (11/02/2014 21:00) and corresponding bed shear stress field.

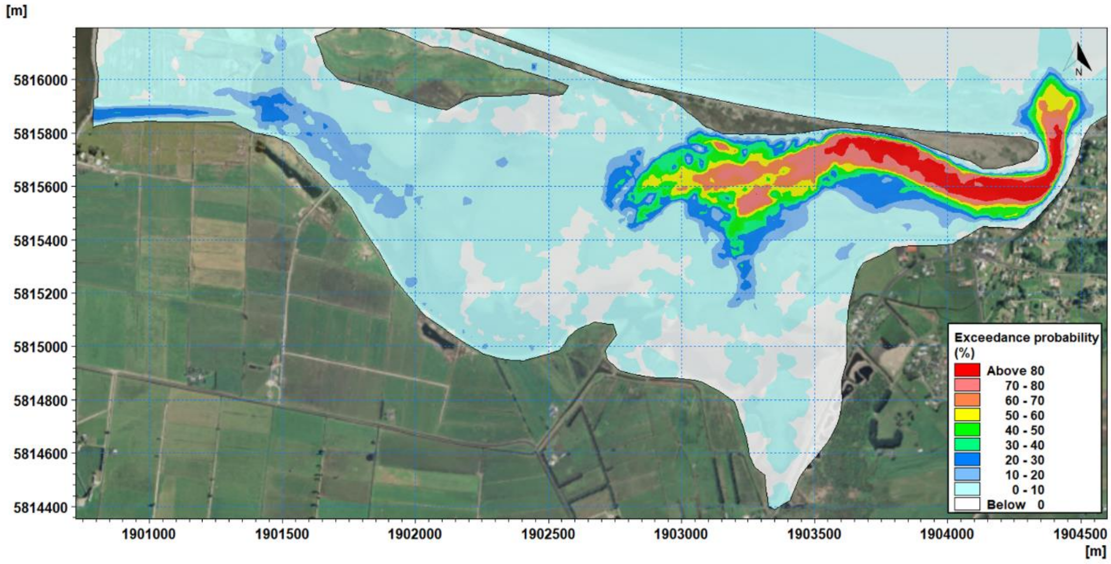

Figure 5-5 Spatial exceedance probability calculate from the model bed shear stress fields saved every hour over 1 year considering a threshold of 0.194 $N.m^{-2}$. This threshold represents the critical bed shear stress for resuspension of medium sand particles as defined in Table 5-1.

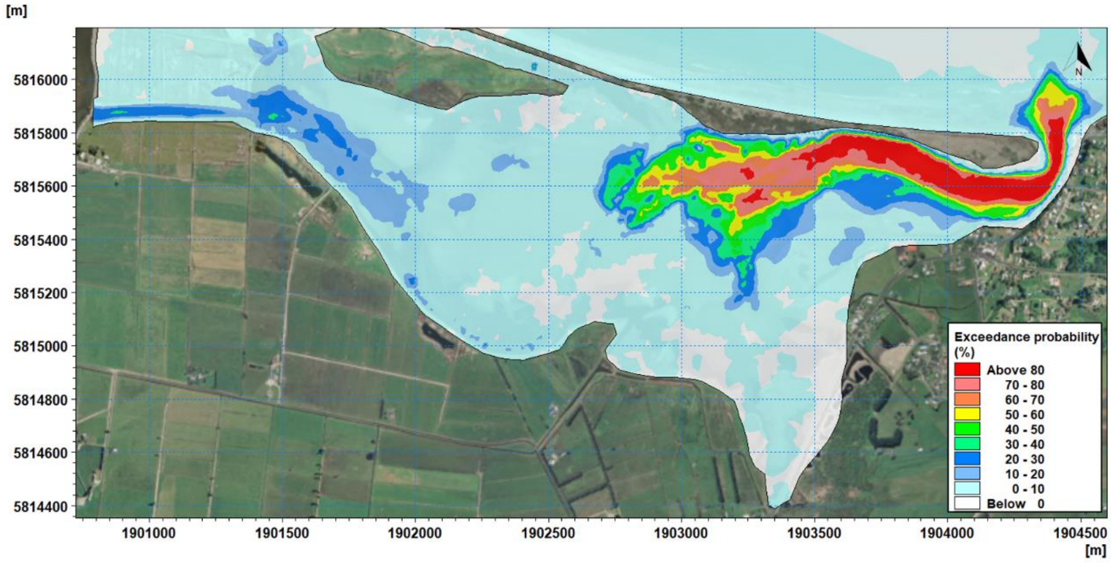

Figure 5-6 Spatial exceedance probability calculate from the model bed shear stress fields saved every hour over 1 year considering a threshold of 0.145 $N.m^{-2}$. This threshold represents the critical bed shear stress for resuspension of fine sand particles as defined in Table 5-1.

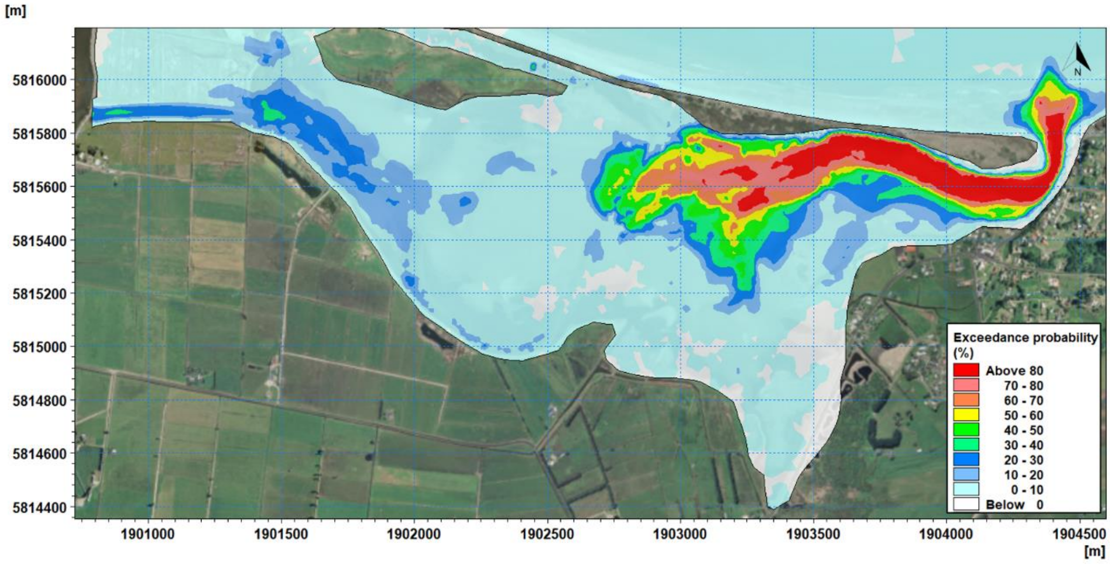

Figure 5-7 Spatial exceedance probability calculate from the model bed shear stress fields saved every hour over 1 year considering a threshold of 0.110 N.m^{-2}. This threshold represents the critical bed shear stress for resuspension of very fine sand particles as defined in Table 5-1.

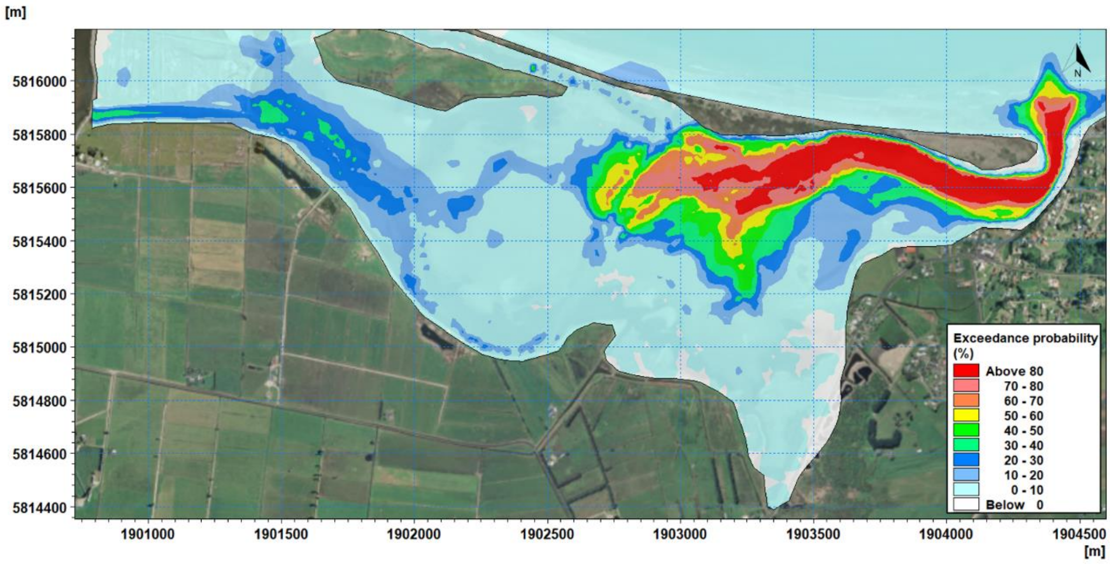

Figure 5-8 Spatial exceedance probability calculate from the model bed shear stress fields saved every hour over 1 year considering a threshold of 0.083 N.m^{-2}. This threshold represents the critical bed shear stress for resuspension of medium silt particles as defined in Table 5-1.

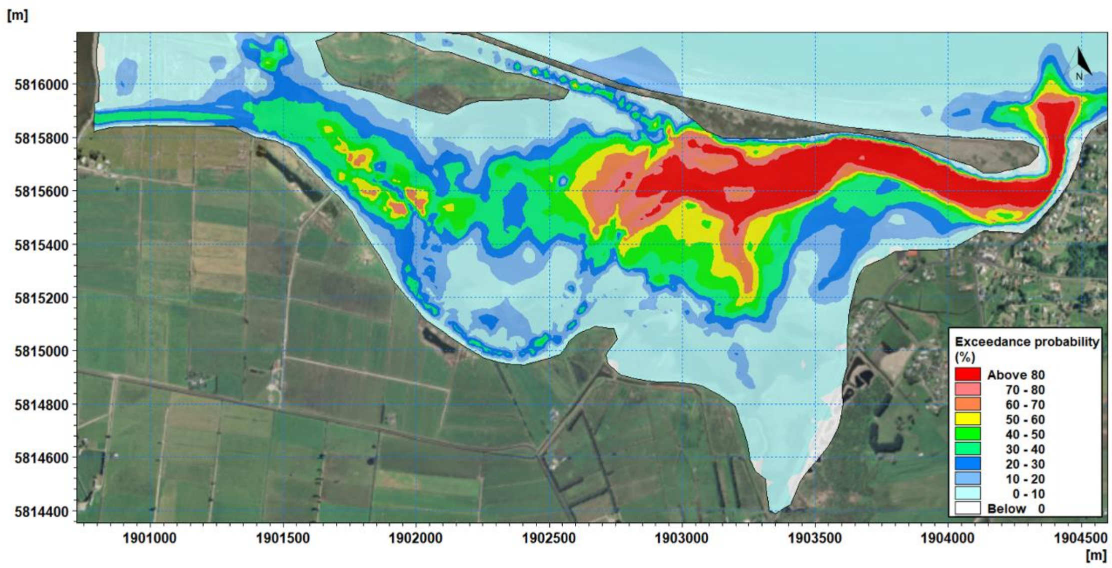

Figure 5-9 Spatial exceedance probability calculate from the model bed shear stress fields saved every hour over 1 year considering a threshold of 0.038 $N.m^{-2}$. This threshold represents the critical bed shear stress for resuspension of clay particles as defined in Table 5-1.

Figure 5-10 Mud fraction obtained by sediment samplings over Maketū Estuary

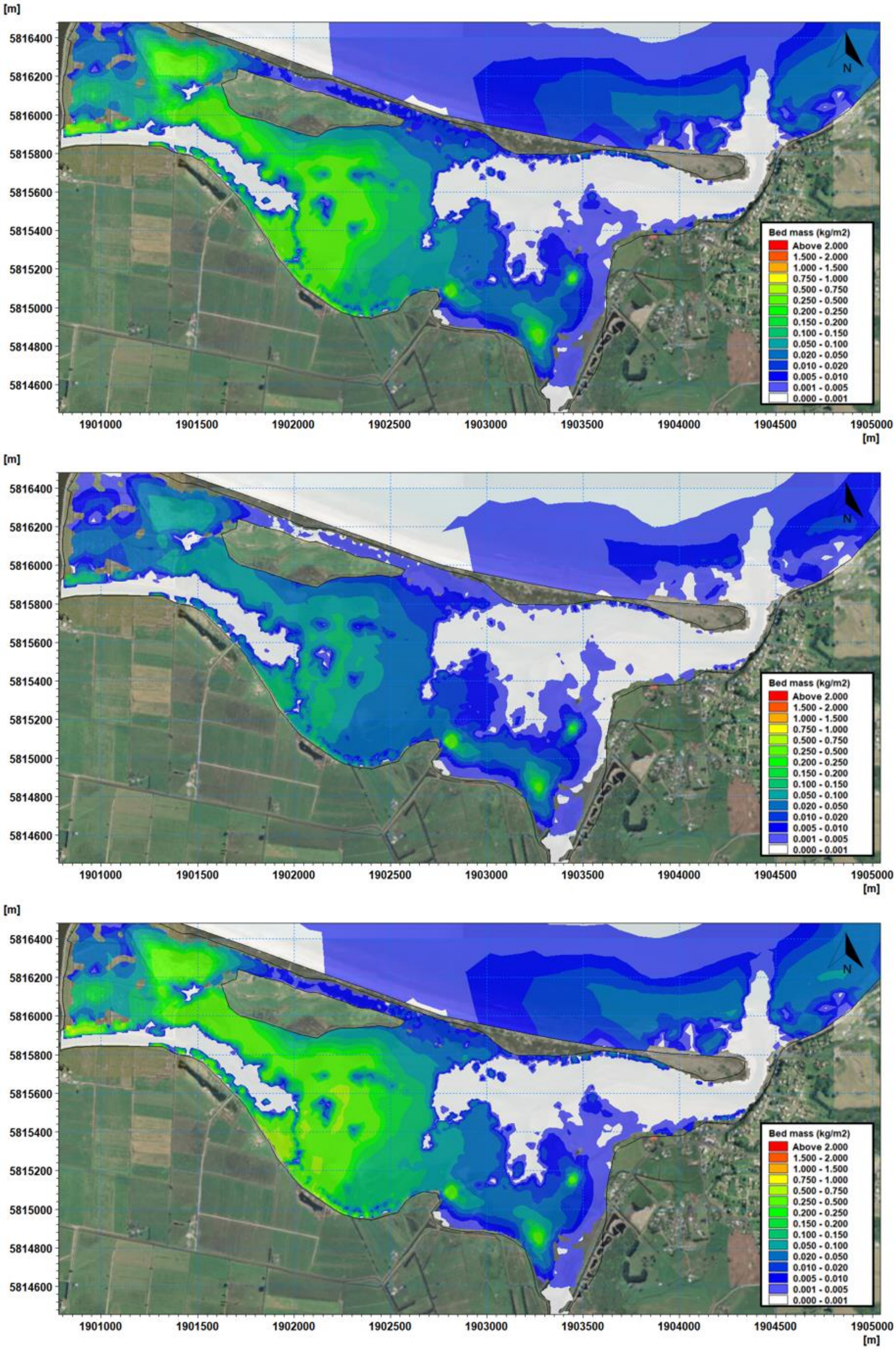

Figure 5-11 Predicted clay mass deposition over 1 year within Maketū Estuary and the adjacent coastal area for Baseline (top panel), Scenario 1 (middle panel) and Scenario 2 (bottom panel).

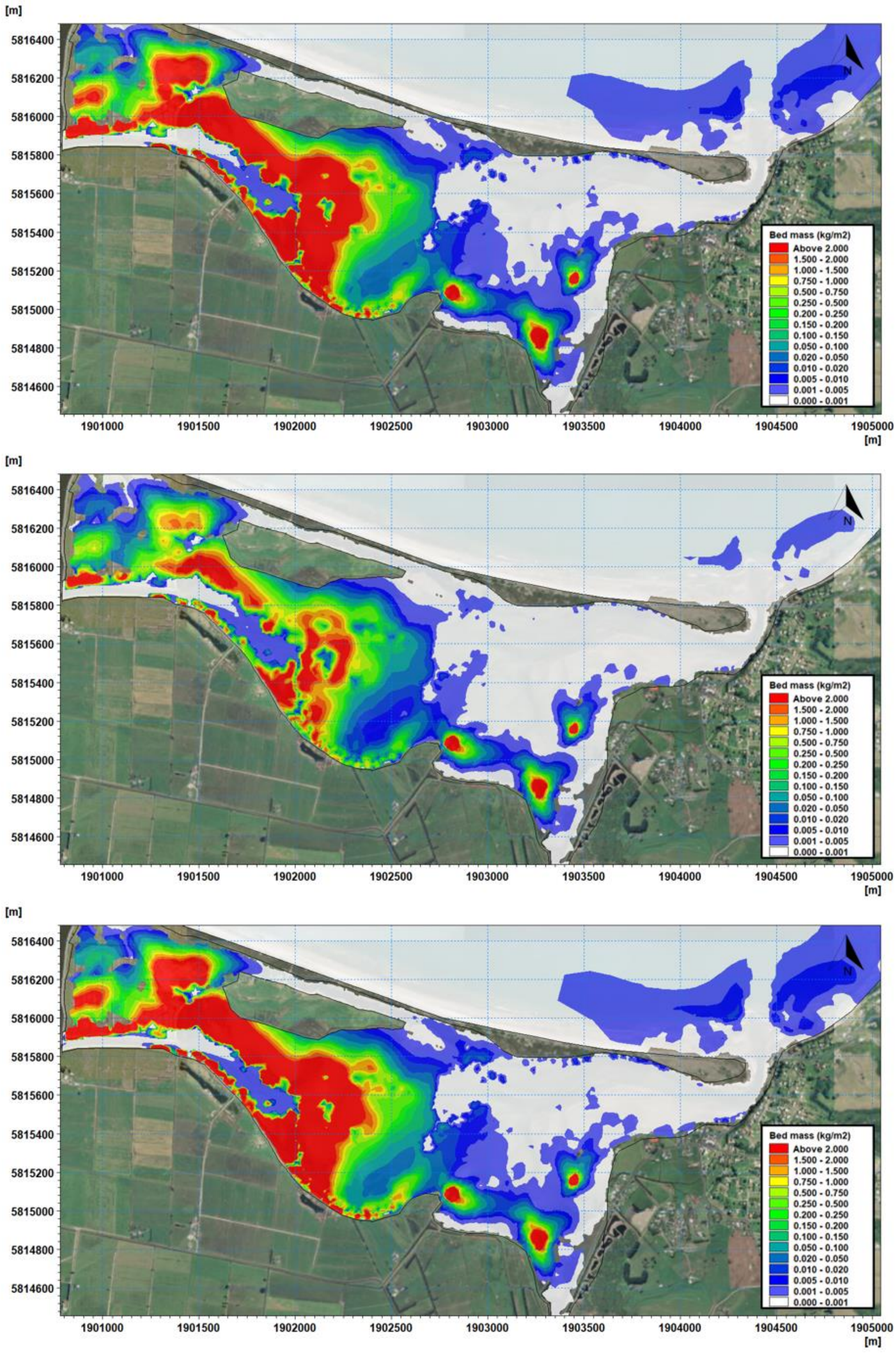

Figure 5-12 Predicted silt mass deposition over 1 year within Maketū Estuary and the adjacent coastal area for Baseline (top panel), Scenario 1 (middle panel) and Scenario 2 (bottom panel).

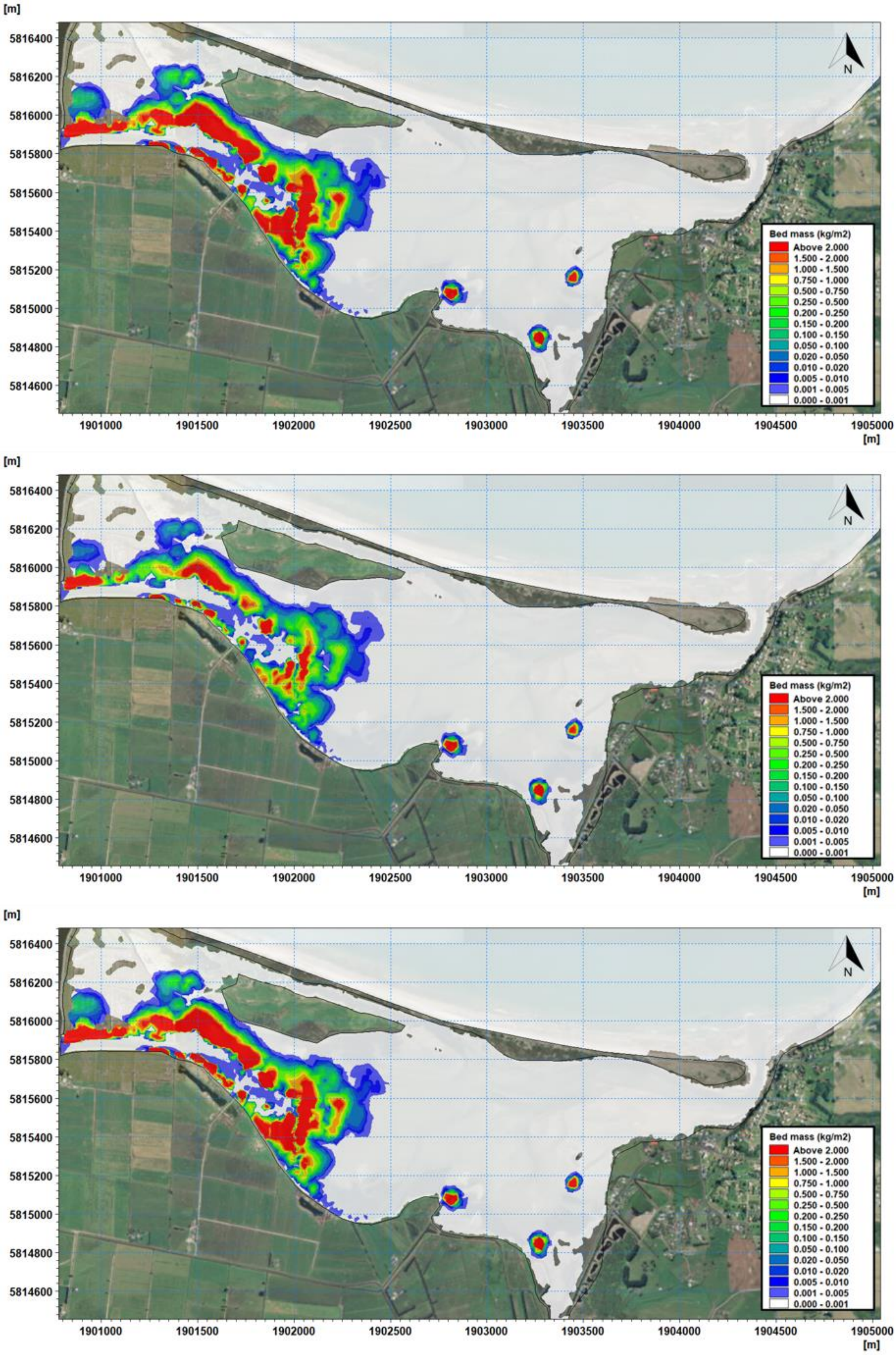

Figure 5-13 Predicted very fine sand mass deposition over 1 year within Maketū Estuary and the adjacent coastal area for Baseline (top panel), Scenario 1 (middle panel) and Scenario 2 (bottom panel).

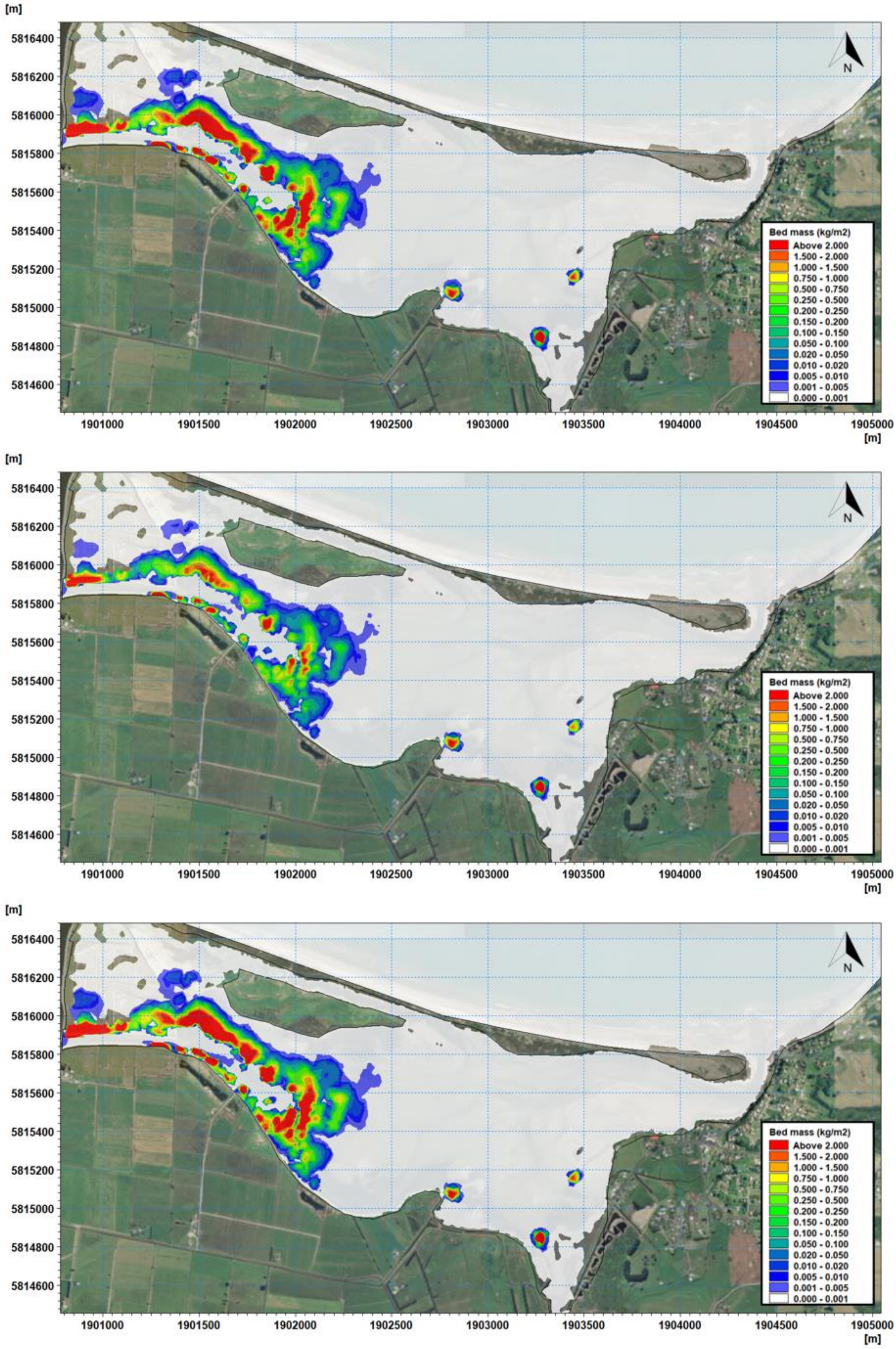

Figure 5-14 Predicted fine sand mass deposition over 1 year within Maketū Estuary and the adjacent coastal area for Baseline (top panel), Scenario 1 (middle panel) and Scenario 2 (bottom panel).

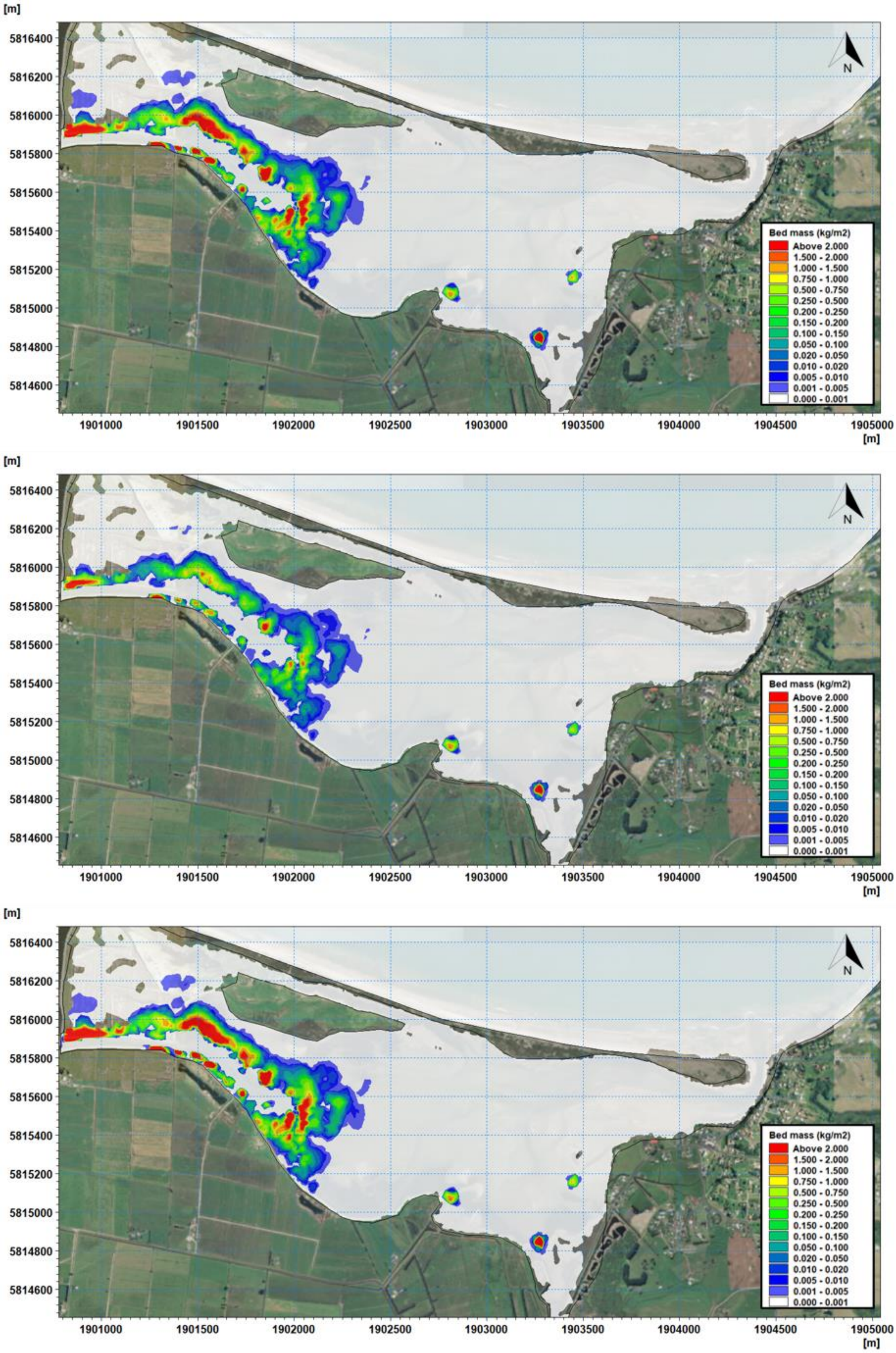

Figure 5-15 Predicted medium sand mass deposition over 1 year within Maketū Estuary and the adjacent coastal area for Baseline (top panel), Scenario 1 (middle panel) and Scenario 2 (bottom panel).

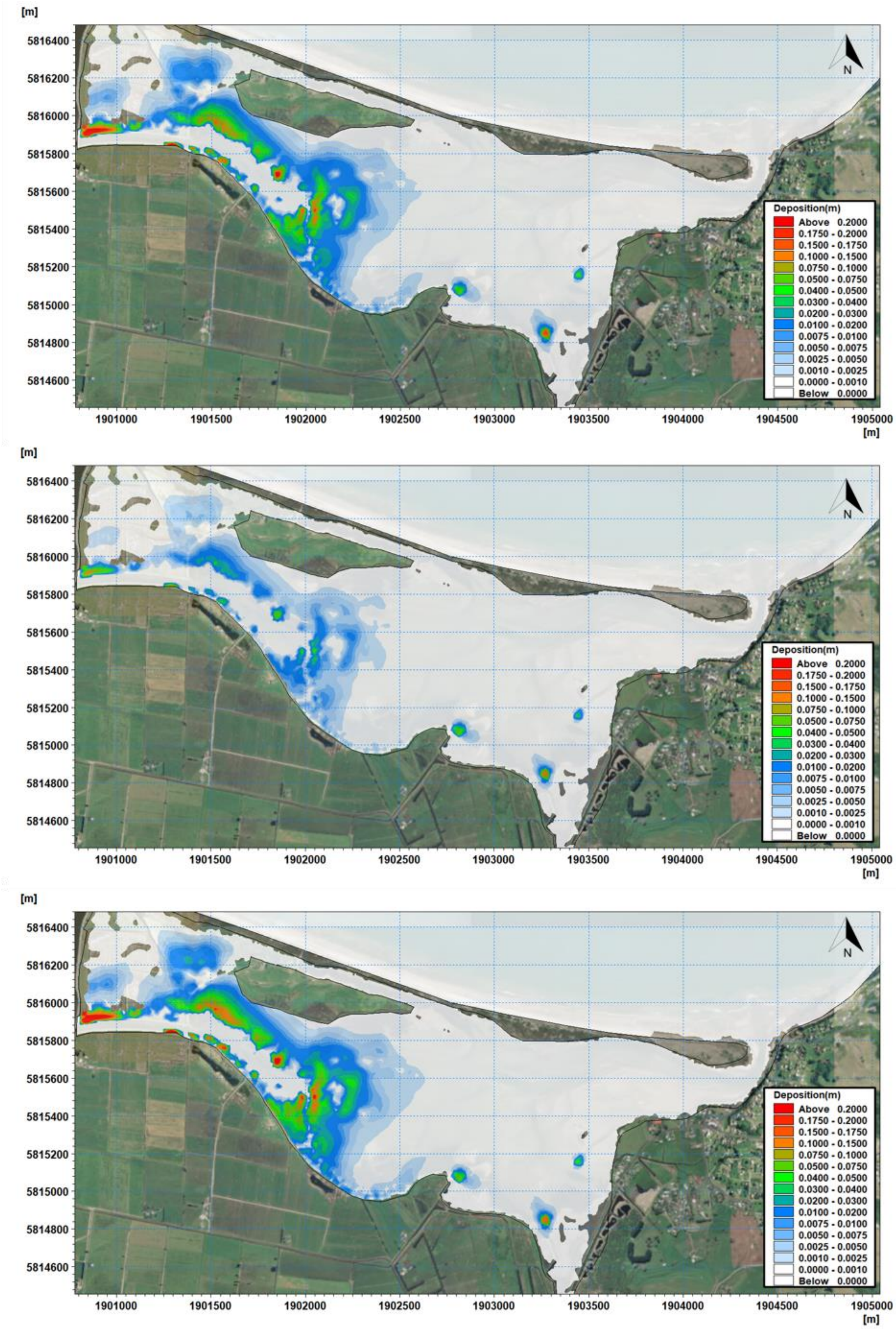

Figure 5-16 Predicted thickness deposition over 1 year considering the five sediment fractions (clay, silt, very fine sand, fine sand, medium sand) within Maketū Estuary for Baseline (top panel), Scenario 1 (middle panel) and Scenario 2 (bottom panel).

A summary of the area of deposition for selected sedimentation thresholds for each scenario is presented in Table 5-2, while Table 5-3 presents the percentage of Maketū Estuary above the selected sedimentation thresholds, assuming an estuary area of 2,424,500 m^2.

Table 5-2 Area of deposition (m^2) in Maketū Estuary for selected sedimentation thresholds and percentage difference from baseline.

Sedimentation Threshold	Scenario				
	Baseline	Scenario 1	% Difference	Scenario 2	% Difference
1 mm/y	764,820	523,700	-31.5	801,000	4.7
2 mm/y	618,400	388,880	-37.1	654,700	5.9
5 mm/y	454,630	195,980	-56.9	486,800	7.1
10 mm/y	321,050	88,850	-72.3	362,100	12.8

Table 5-3 Percentage of Maketū Estuary above selected sedimentation thresholds.

Sedimentation Threshold	Scenario		
	Baseline	Scenario 1	Scenario 2
1 mm/y	31.5	21.6	33.0
2 mm/y	25.5	16.0	27.0
5 mm/y	18.8	8.1	20.1
10 mm/y	13.2	3.7	14.9

Current research (Robertson et al., 2016), suggests an estuary with a mud content of greater than 25% over less than 1% of its area can be considered A grade in terms of ecology ("No Stress"), a B grade is achieved if greater than 25% mud content occurs over 1 to 5% of the estuary ("Minor stress") and a C grade is associated with an estuary where more than 25% mud content occurs over 5-15% of the estuary ("Moderate stress").

If the predicted sedimentation patterns under the Baseline or Scenario 2, were to continue in the long term, there would be a concern the Ecological Quality Grading for the Maketū Estaury may move from a B to a C. However, since the estuary is predicted to have a significant morphological response to the new hydrodynamic regime, it is likely the grading will remain the same. The results indicate that Scenario 2 would have a small (but still undesirable) impact on predicted sedimentation rates within the estuary.

The reduction in sediment load for Scenario 1 (Naturalised state), leads to a significant reduction in sedimentation within the estuary (i.e. the area with sedimentation greater than 1 cm decreases from 13% to 4% of the estuary).This level of reduction is unlikely to improve the estuary to an A Grading.

5.2 Water Quality Results

This section describes results from water quality modelling with respect to assessments of bacteria, nutrients, macroalgae, and seagrass. As the modelling of Maketū Estuary corresponds to post Kaituna River re-diversion , no comparison against field measurements was carried out due to lack of relevant observations.

Results discussed in the following sub-sections refer to different regions of the estuary as shown in Figure 5-17.

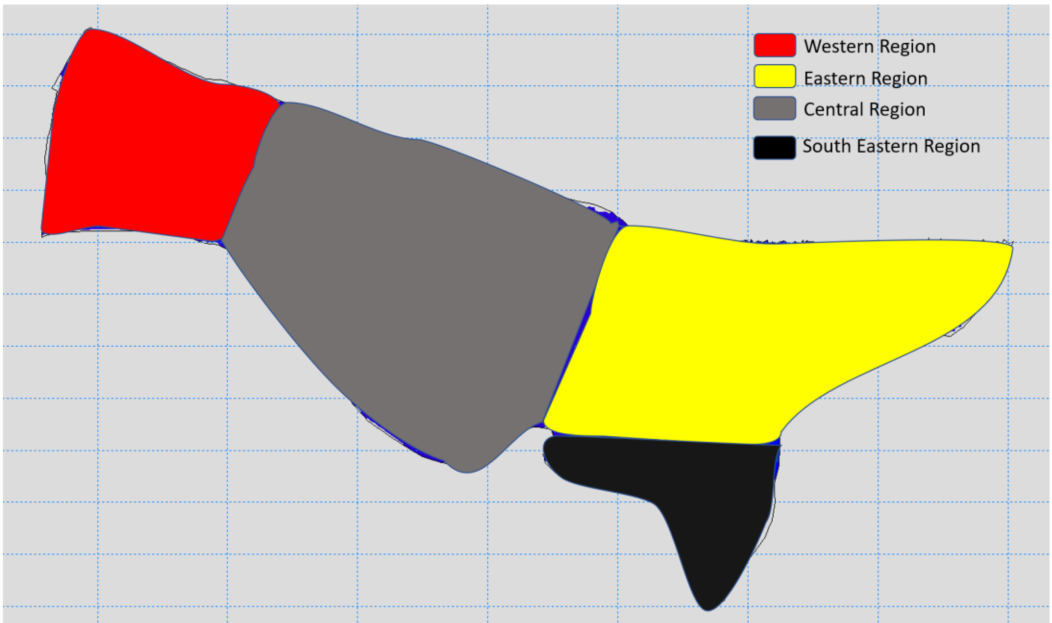

Figure 5-17 Different regions of the Maketū Estuary.

5.2.1 Bacteria Assessment

Figure 5-18 shows the 95th percentile plot of E.cocci for Baseline, Scenario 1, and Scenario 2 results respectively.

E.cocci levels below the guideline value of 280 cfu/100ml[12] are observed across the majority of the estuary in all three scenarios.

E.cocci levels higher than the guideline value are observed in Baseline and Scenario 2 in the south eastern region of the Maketū Estuary.

[12] Microbiological Water Quality Guidelines state that for estuaries to be safe for primary contact recreation/bathing, the concentration of E.cocci must not exceed 280 cfu/100ml.

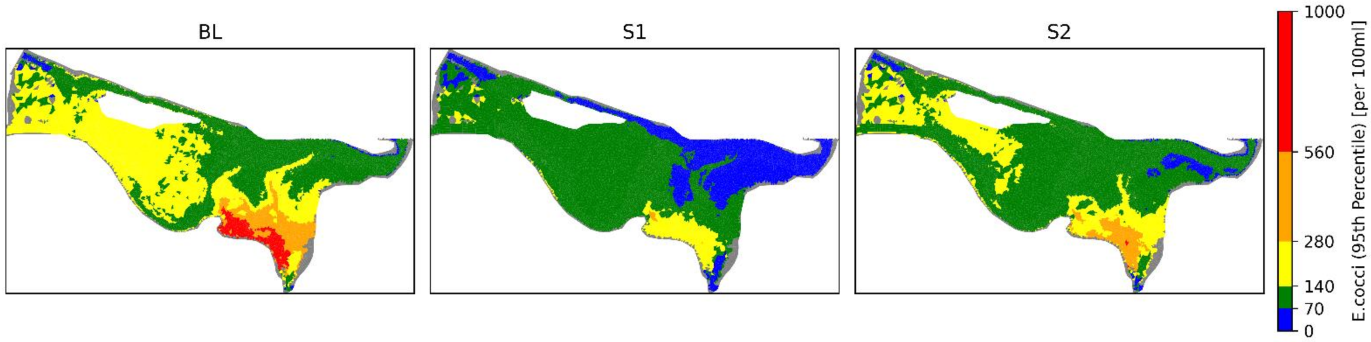

Figure 5-18 95th percentile (E.cocci) in Maketū Estuary. BL corresponds to Baseline, S1 corresponds to Scenario 1, and S2 corresponds to Scenario 2.

Figure 5-19 shows the difference plots of the 95th percentile results of Scenario 1 and 2 as compared to baseline model results. The figure quantifies the decrease (in percentage) in predicted E.cocci levels in different regions of the estuary.

Annual and seasonal analysis of the predicted E.cocci levels in the estuary with respect to meeting microbiological water quality guidelines for primary contact recreation/bathing was carried out.

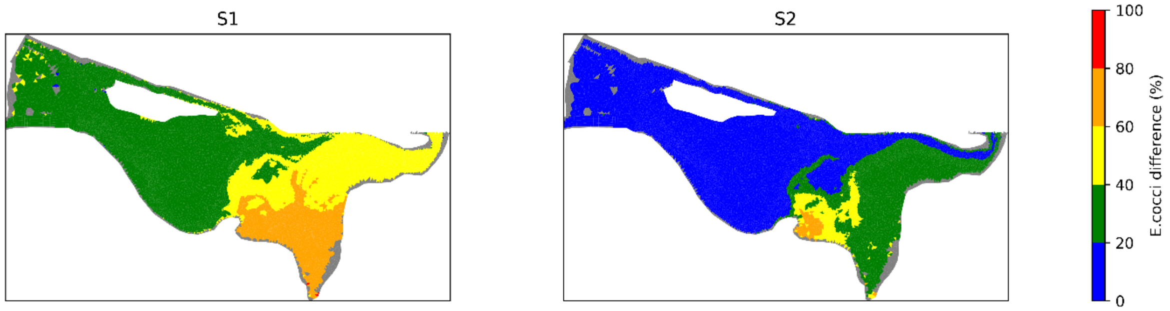

Figure 5-19 Difference (decrease) plots of 95th percentile (E.cocci) in Maketū Estuary. S1 corresponds to Scenario 1 and S2 corresponds to Scenario 2.

Figure 5-20 and Figure 5-21 show the spatial plots for the three scenarios for annual and each of the four seasons respectively. Both the plots show the percentage of time exceedance - above the guideline value of 280 cfu/100 ml - is predicted during each period.

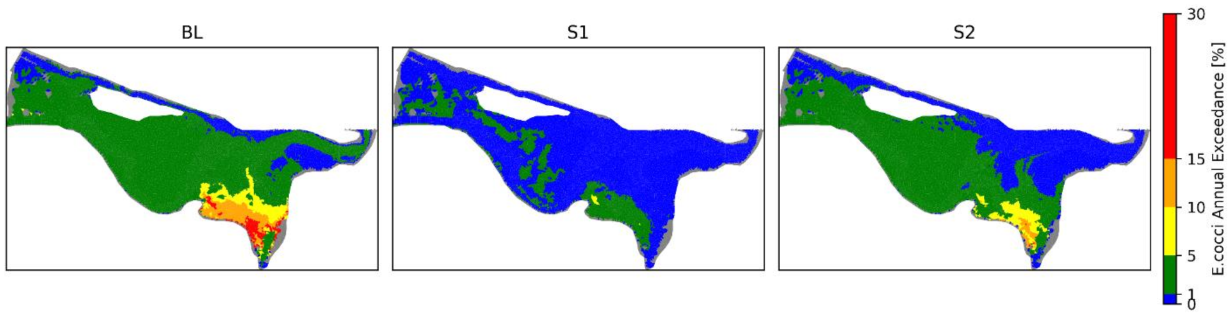

Figure 5-20 Percentage of exceedance of E.cocci levels above 280 cfu/100ml (annual). BL corresponds to Baseline, S1 corresponds to Scenario 1, and S2 corresponds to Scenario 2.

In Figure 5-20, in all three simulations, we observe that the E.cocci levels meet the guideline value for more than 95% of annual period for most of the estuary.

In Baseline, in the spatial area near the three sources (56, 58, and 59) in the south eastern region of the estuary, we observe E.cocci levels exceed the guideline value for more than 15% of annual period.

This part of the estuary is characterized by shallower water depths. Shallower water depths mean less dilution as well as less flushing due to subsequent dilution. This leads to more E.cocci loads retained near the sources.

In terms of levels of exceedance, order observed is Scenario 1 < Scenario 2 < Baseline.

With respect to seasonal analysis, as shown in Figure 5-21, in Scenario 1, we observe that the E.cocci levels meet the guideline value for 99% of spring, summer, and autumn periods across the estuary.

In winter, we observe E.cocci levels exceed the guideline value for less than 5% of the season across most of the estuary.

In Baseline and Scenario 2, we observe that the E.cocci levels meet the guideline value for 99% of spring and summer periods across the estuary.

In winter, we observe that the E.cocci levels exceed the guideline value for more than 5% of the season in western, central, and south eastern regions of the estuary.

In terms of seasonal exceedance, order observed is Winter > Autumn > Summer > Spring

We also observe that areas downstream of Kaituna River inflows show E.cocci levels exceed the guideline value for more than 5% of time in winter season in only Baseline and Scenario 2 runs.

Interestingly, although the amount of E.cocci loads contributed by the Kaituna River form more than 90% of the total loads, higher levels of E.cocci exceedance are not predicted in the area downstream of the culvert.

To determine the target reduction of baseline catchment loads to meet the E.cocci guideline value of 280 cfu/100 ml across the estuary, statistical regression analysis was performed.

Exponential regression between 95th percentile E.cocci levels in the estuary and 95th Percentile daily E.cocci loads to the estuary estimated that a 20.39% reduction of baseline catchment loads is required for E.cocci levels across the whole of the Maketū estuary to meet the guideline value.

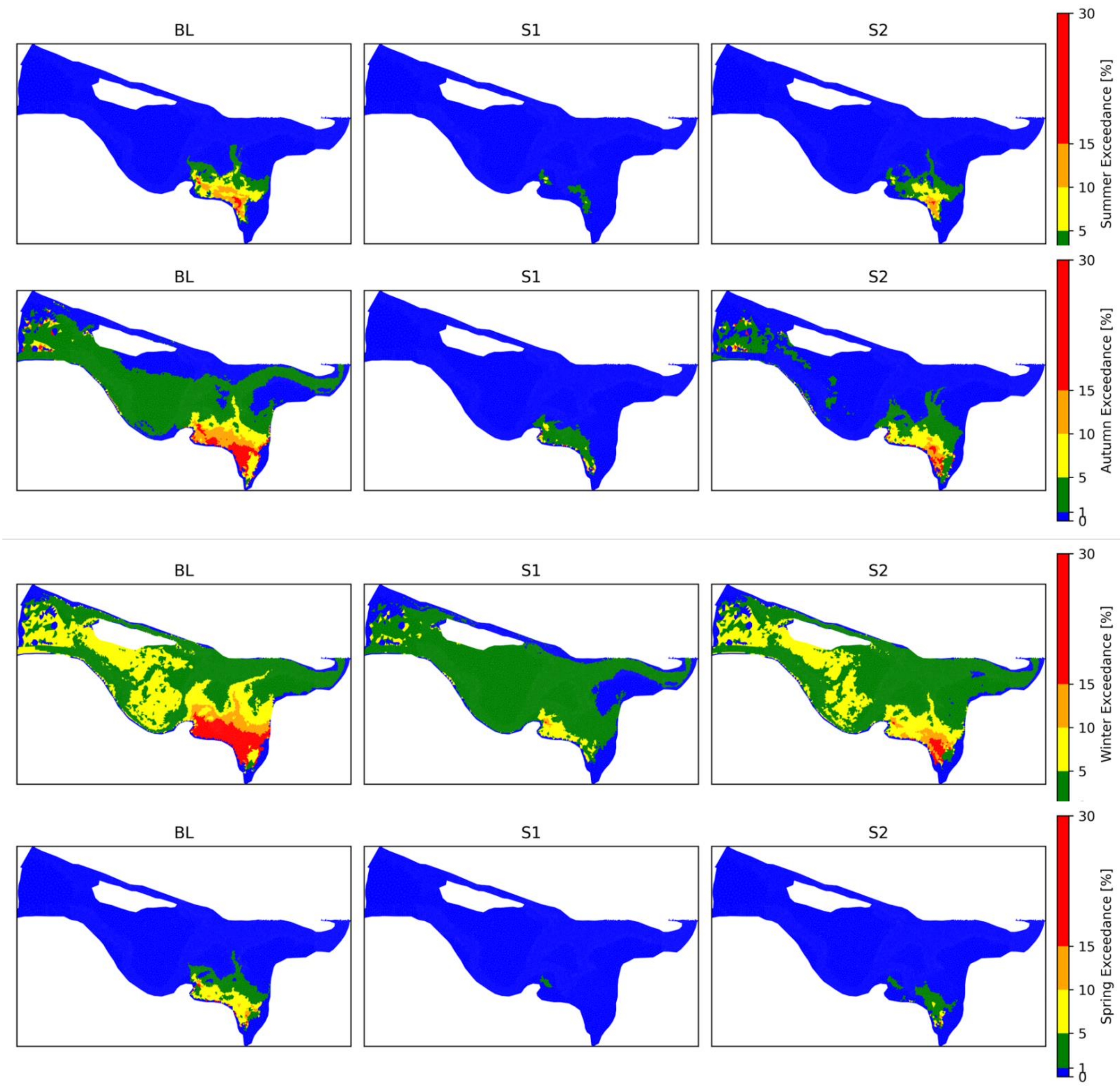

Figure 5-21 Percentage of exceedance of E.cocci above 280 cfu/100 ml in Summer (top), Autumn (middle-top), Winter (middle-bottom) and Spring (bottom). BL corresponds to Baseline, S1 corresponds to Scenario 1, and S2 corresponds to Scenario 2.

Figure 5-22 shows the 50th percentile plot of F.coli for Baseline, Scenario 1, and Scenario 2 results respectively.

F.coli levels below the guideline value of 14 MPN/100ml[13] are observed across most of the estuary in all three scenarios.

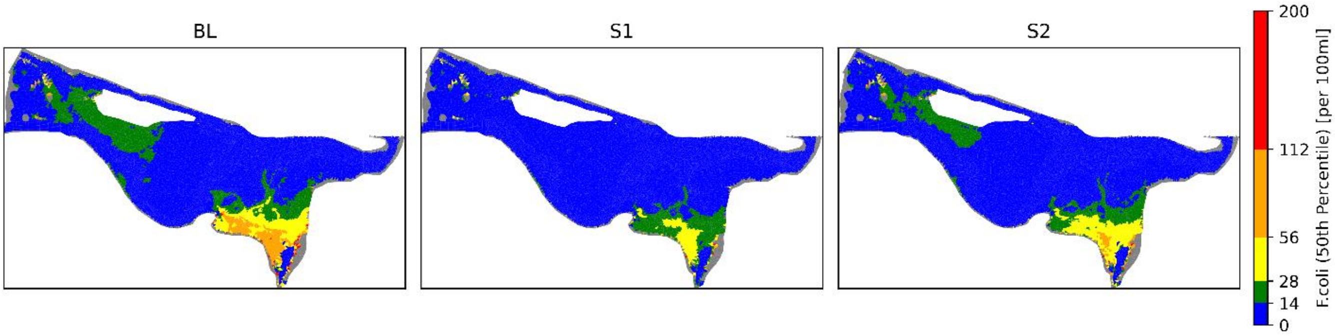

Figure 5-22 50th percentile spatial plots of F.coli in Maketū Estuary. BL corresponds to Baseline, S1 corresponds to Scenario 1, and S2 corresponds to Scenario 2.

Figure 5-23 shows the difference plots of the 50th percentile results of Scenario 1 and 2 as compared to baseline model results. The figure quantifies the decrease (in percentage) in predicted F.coli levels in different regions of the estuary.

Guidelines indicate that not more than 10% of F.coli samples should exceed 43 per 100 mL (MfE, 2003).

Annual and seasonal analysis of the F.coli levels in the estuary with respect to meeting this guideline was carried out.

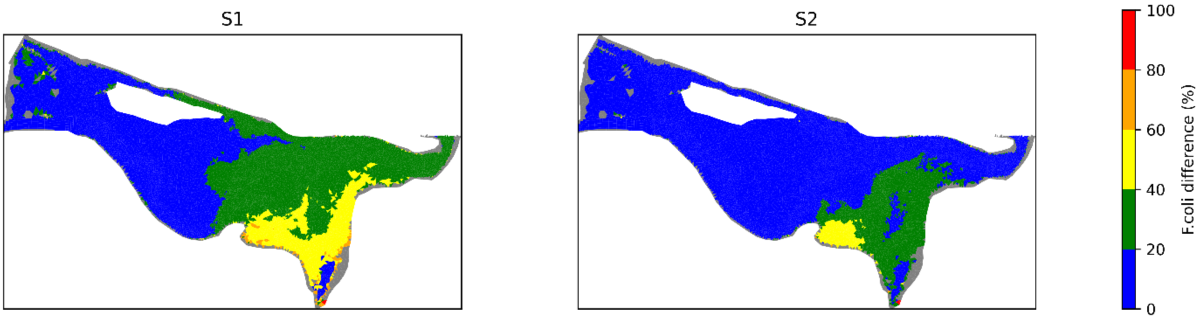

Figure 5-23 Difference (decrease) plots of 50th percentile (F.coli) in Maketū Estuary. S1 corresponds to Scenario and S2 corresponds to Scenario 2 respectively.

Figure 5-24 and Figure 5-25 show the spatial plots for the three scenarios for annual and each of the four seasons respectively. Both the plots show the percentage of time exceedance - above the guideline value of 43 per 100 ml - is predicted during each period.

[13] For Kaimoana to be safe to eat, the median faecal coliform content of water samples taken over a shellfish-gathering season shall not exceed a Most Probable Number (MPN) of 14/100 mL, and not more than 10% of samples should exceed an MPN of 43/100 mL (using a five-tube decimal dilution test).

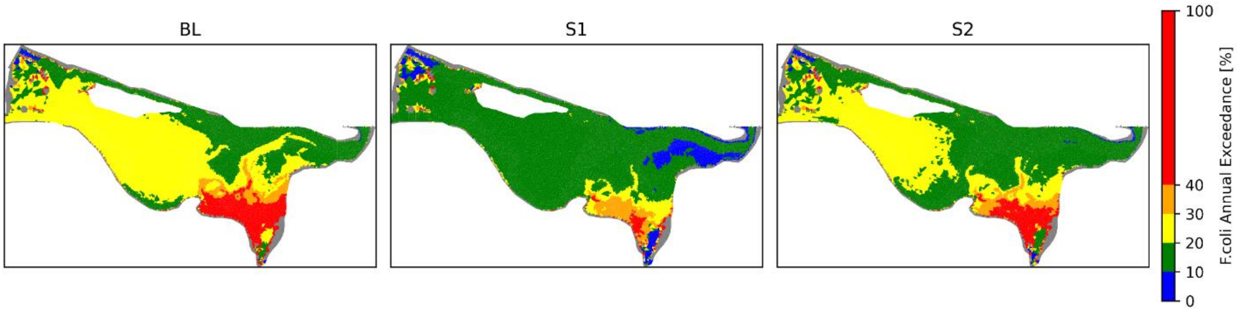

Figure 5-24 Percentage of exceedance of F.coli levels (annual). BL corresponds to Baseline, S1 corresponds to Scenario 1, and S2 corresponds to Scenario 2.

In Figure 5-24, in Scenario 1, we observe F.coli levels exceed the guideline value for less than 20% of annual period for most of the estuary.

In Baseline and Scenario 2, we observe F.coli exceed the guideline value for less than 30% of annual period for most of the estuary.

In all three scenarios, in the spatial area near the three sources (56, 58, and 59) in the south eastern region of the estuary, we observe F.coli levels exceed the guideline value for more than 40% of annual period.

In terms of levels of exceedance, order observed is Scenario 1 < Scenario 2 < Baseline.

With respect to seasonal analysis, as shown in Figure 5-25, in Scenario 1, we observe that most of the estuary meets the guideline value for summer period across the estuary. In contrast, during winter, F.coli levels exceed the guideline value for more than 20% of the season across the estuary.

In Baseline and Scenario 2, we observe F.coli exceed the guideline value for less than 20% of spring, summer, and autumn seasons for most of the estuary. In contrast, during winter, F.coli levels exceed the guideline value for more than 30% of the season across the estuary.

In all three scenarios, in each of the four seasons, in the spatial area near the three sources (56, 58, and 59) in the south eastern region of the estuary, we observe F.coli levels exceed the guideline value for more than 40% of annual period. The area of exceedance is lower in Scenario 1 as compared to Scenario 2 and Baseline.

This part of the estuary is characterized by shallower water depths. Shallower water depths mean less dilution as well as less flushing due to subsequent dilution. This leads to higher F.coli levels near the sources.

Downstream of the Kaituna River, F.coli levels exceed the guideline value for more than 40% of time in winter in all three runs.

In rest of the seasons, in Baseline and Scenario 2 runs, F.coli levels exceed the guideline value downstream of Kaituna River for less than 20% of each season.

In terms of seasonal exceedance, order observed is Winter > Autumn > Spring > Summer.

To determine the target reduction of baseline catchment loads to meet the F.coli guideline value of 14 MPN/100 ml across the estuary, statistical regression analysis was performed.

Exponential regression between 50th percentile F.coli levels in the estuary and 50th Percentile daily F.coli loads to the estuary estimated that a 38.87% reduction of baseline catchment loads is required for F.coli levels across the whole of the Maketū Estuary to meet the guideline value.

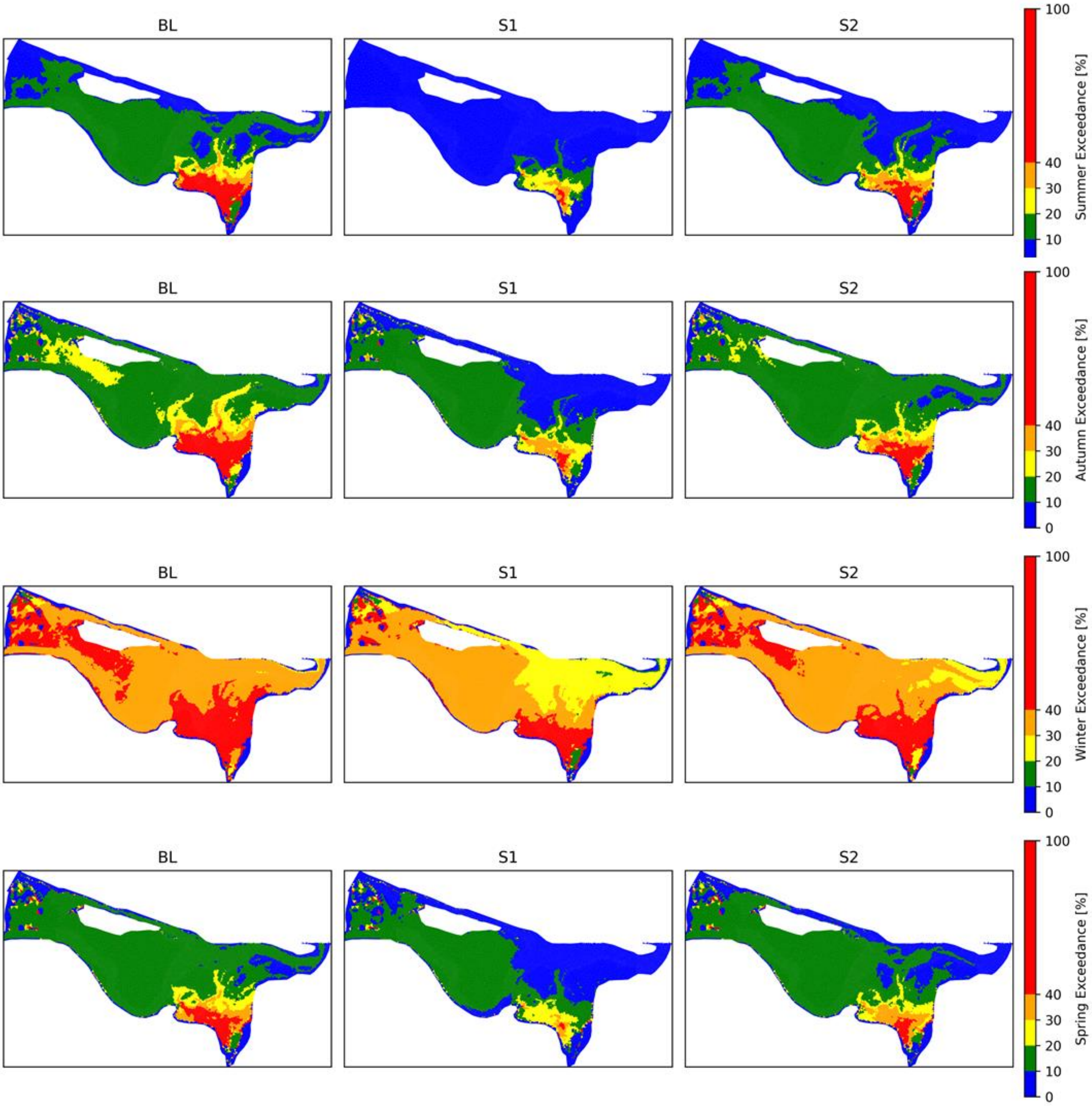

Figure 5-25 Percentage of exceedance (F.coli) in Summer (top), Autumn (middle – top), Winter (middle – bottom) and Spring (bottom). BL corresponds to Baseline, S1 corresponds to Scenario 1, and S2 corresponds to Scenario 2.

5.2.2 Nutrient and Ecological Assessment

Analysis of TN levels in the estuary was carried out against Ministry for the Environment's suggested guidelines for setting instream nutrient concentrations in macroalgal dominated estuarine systems (MfE 2021). The relevant values of potential TN concentration in the estuary categorized to different trophic state bands are shown in Table 5-4 below.

Table 5-4 Trophic State Band in Macroalgal-dominated estuarine systems.

Trophic State Band	Band narrative	Potential TN Concentration .mg/l)
A	Near Reference	<= 0.055
B	Slightly Impacted	>0.055 to <= 0.180
C	Moderately Impacted	>0.180 to <= 0.350
D	Heavily Impacted	>0.350

Figure 5-26 shows the 50th percentile spatial distribution of Total Nitrogen (TN) in the water column of Maketū Estuary for Baseline, Scenario 1, and Scenario 2 results respectively based on the categorizations seen in Table 5-4.

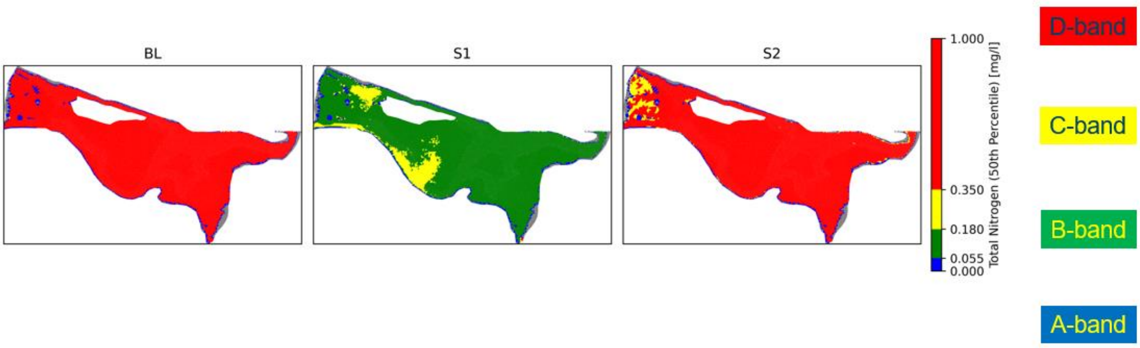

Figure 5-26 50th percentile spatial plots of TN levels in Maketū Estuary. BL corresponds to Baseline, S1 corresponds to Scenario 1, and S2 corresponds to Scenario 2.

In Baseline, the predicted median concentration of TN is above 0.35 mg/l across the estuary. This categorizes Maketū Estuary to Trophic State Band D (heavily impacted).

In Scenario 1, the predicted median concentration of TN is between 0.055 mg/l and 0.18 mg/l for most of the estuary. This categorizes Maketū Estuary to Trophic State Band B (slightly impacted).

In Scenario 2, the predicted median concentration of TN is above 0.35 mg/l in most of the estuary. This categorizes Maketū Estuary to Trophic State Band D (heavily impacted).

To determine the target reduction of baseline catchment loads of TN for the estuary to move from Band D to Band C or Band B trophic state, statistical regression analysis was performed. Annual median of TN concentrations in the estuary as predicted by the Eutrophication model was computed. An estuary wide spatial median of the above results was derived and regressed against catchment loads. Linear regression gave a better fit. Table 5-5 shows the catchment load reductions (from baseline) for Maketū Estuary

Table 5-5 Target catchment load reductions from baseline

Trophic State Band	TN (mg/L)	Target TN Concentration (mg/L)	Target Catchment Load (mg/m2/d)	Target Catchment Load Reduction (%) from Baseline
A	<= 0.055	0.055 (Max Band A)	68.5	92.48
B	>0.055 to <= 0.180	0.1175 (Mid - Band B)	146.63	83.91
		0.18 (Max - Band B)	224.75	75.34
C	>0.180 to <= 0.350	0.265 (Mid - Band C)	331	63.68
		0.35 (Max - Band C)	437.25	52.02

ETI Tool 1 (Robertson 2016a) has the following banding table (Table 5-6) for nutrient load susceptibility and trophic states –

Table 5-6 ETI Tool 1 banding for nutrient load susceptibility and trophic state

		N load Susceptibility (mg/m²/d)			
Physical Susceptibility		Very High >250	High >50-250	Moderate 10-50	Low <10
	High	Band D Very High	Band C High	Band C High	Band B Moderate
	Mod	Band D Very High	Band C High	Band B Moderate	Band A Low
	Low	Band C High	Band B Moderate	Band B Moderate	Band A Low

To align with these values, following catchment load reductions (from baseline) are computed from model predictions (using the same steps as listed above) –

Table 5-7 ETI Tool 1 target catchment load reductions from baseline

Band	Catchment Nitrogen Load (mg/m2/d)	Catchment Nitrogen Load (mg/m2/d)	Target Catchment Load Reduction (%) from Baseline
A	<=10	10 (Max Band A)	98.9
B	>10 to <=50	30 (Mid - Band B)	96.71
		50 (Max - Band B)	94.51
C	>50 to <=250	150 (Mid - Band C)	83.54
		250 (Max - Band C)	72.57

Figure 5-27 shows the difference plots of the 95th percentile results of Scenario 1 and 2 as compared to baseline model results. The figure quantifies the decrease (in percentage) in predicted TN levels in different regions of the estuary.

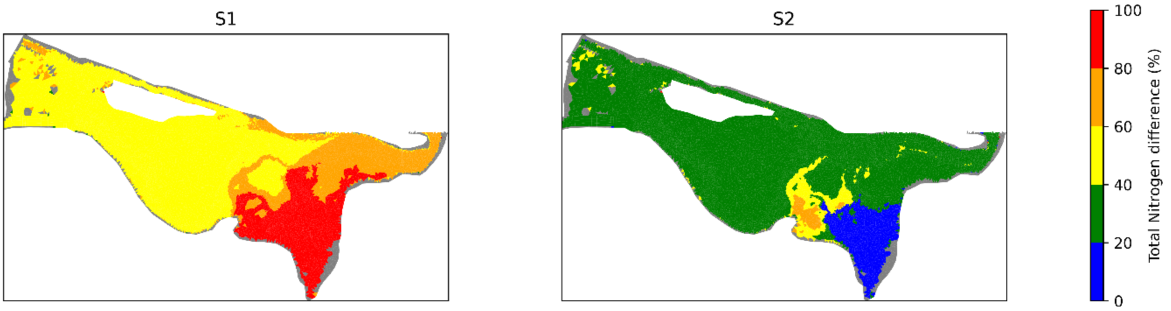

Figure 5-27 Difference (decrease) plots of 95th percentile (Total Nitrogen) in Maketū Estuary. S1 corresponds to Scenario 1 and S2 corresponds to Scenario 2 respectively.

Total Nitrogen loads discharging into Maketū Estuary in 2014 are 1140 tonnes/year, 366 tonnes/year, and 699 tonnes/year under the Baseline, Scenario 1, and Scenario 2 runs respectively.

After the uptake and transformation of these nitrogen loads in the estuary, the amount of nitrogen deposited in the sediment layer of Maketū Estuary at the end of annual simulation for the each of the model runs in shown in Figure 5-28.

In all three runs, we observe that deposition of more than 25 gN/m^2 is predicted to occur predominantly in the central region of the estuary.

Deposition rates of less than 10 gN/m^2 are predicted to occur in the eastern region of the estuary in all three runs.

The total mass of TN loads deposited across the estuary is predicted to be 59.7 tonnes/year, 43 tonnes/year, and 59.3 tonnes/year for the Baseline, Scenario 1, and Scenario 2 simulations respectively.

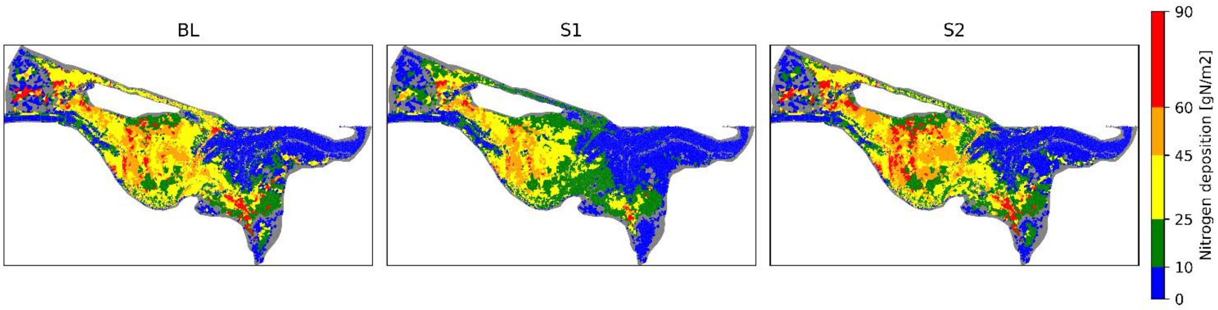

Figure 5-28 Spatial distribution of nitrogen deposition in sediment layer of Maketū Estuary. BL corresponds to Baseline, S1 corresponds to Scenario 1, and S2 corresponds to Scenario 2

Figure 5-29 shows the spatial plot of internal nitrogen loading in Maketū Estuary.

Internal loading of less than 5 gN/m^2 is predicted to be released from sediment to water column across the eastern and south-eastern regions of the estuary in all three scenarios.

The nitrogen efflux (from the sediment to water column) is predicted to be 16.56 tonnes/yr, 10.51 tonnes/yr, and 15.39 tonnes/yr for the Baseline, Scenario 1, and Scenario 2 simulations respectively.

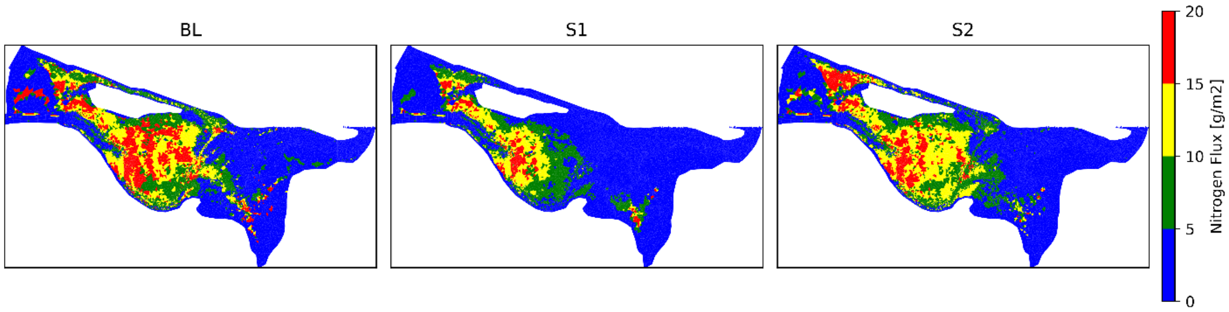

Figure 5-29 Spatial plots of internal nitrogen loading in Maketū Estuary. BL corresponds to Baseline, S1 corresponds to Scenario 1, and S2 corresponds to Scenario 2.

Figure 5-30 shows the 95th percentile spatial distribution of Total Phosphorous (TP) levels in the water column of Maketū Estuary for Baseline, Scenario 1, and Scenario 2 results respectively.

Predicted levels of TP are less than 0.04 mg/l across most of the estuary in Scenario 1 whereas levels are above 0.04 mg/l across most of the estuary in Scenario 2.

Predicted levels of TP in the south eastern region of the estuary are higher than 0.16 mg/l for the Baseline and Scenario 2 runs respectively. This is the area in the vicinity of the sources

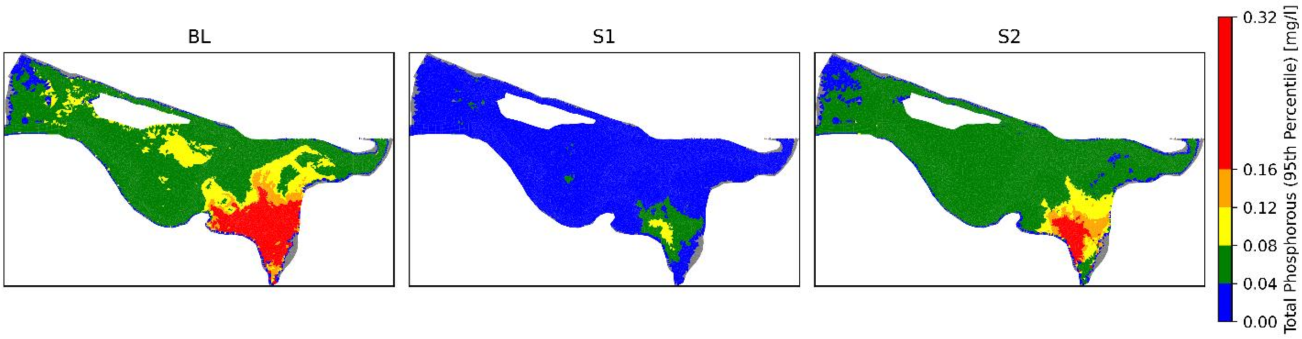

Figure 5-30 95th percentile spatial plots of Total Phosphorous in Maketū Estuary. BL corresponds to Baseline, S1 corresponds to Scenario 1, and S2 corresponds to Scenario 2.

Figure 5-31 shows the difference plots of the 95th percentile results of Scenario 1 and 2 as compared to baseline model results. The figure quantifies the decrease (in percentage) in predicted TP levels in different regions of the estuary.

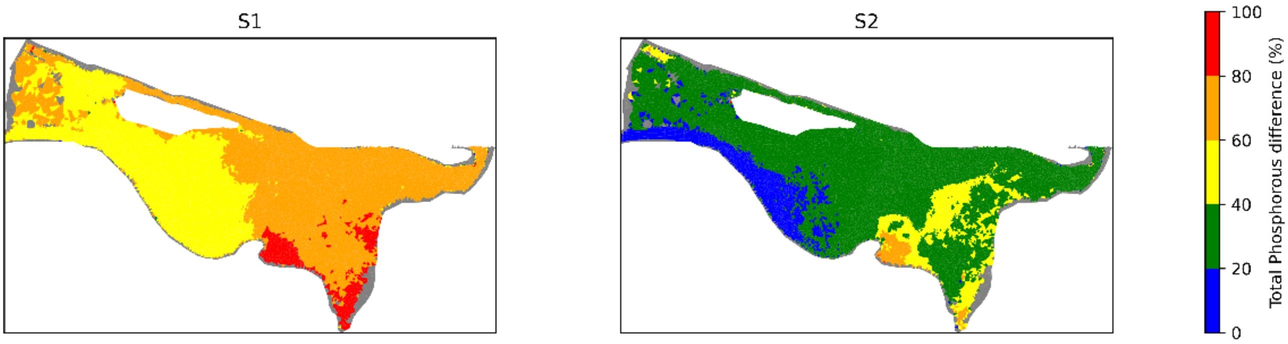

Figure 5-31 Difference (decrease) plots of 95th percentile (Total Phosphorous) in Maketū Estuary. S1 corresponds to Scenario 1 and S2 corresponds to Scenario 2.

The Total Phosphorous loads discharging into Maketū Estuary are 49.1 tonnes/year, 24.2 tonnes/year, and 41.5 tonnes/year under the Baseline, Scenario 1, and Scenario 2 respectively.

After the uptake and transformation of these phosphorous loads in the estuary, the amount of phosphorous deposited in the sediment layer of Maketū Estuary at the end of annual simulation for the each of the model runs in shown in Figure 5-32.

In all three runs, less than 2 gP/m^2 of deposition is predicted to occur in eastern region of the estuary.

In all three runs, deposition of more than 4 gP/m^2 is predicted to occur predominantly in the central portion of the estuary.

The total mass of Total Phosphorous deposited across the estuary is predicted to be 7.7 tonnes/year, 5.8 tonnes/year, and 7.5 tonnes/year for the Baseline, Scenario 1, and Scenario 2 simulations respectively.

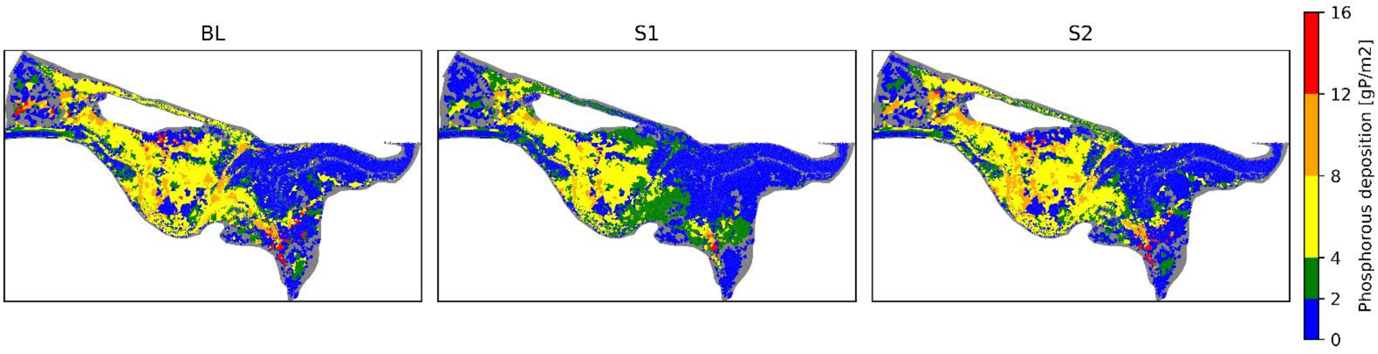

Figure 5-32 Spatial distribution of phosphorous deposition in sediment layer of Maketū Estuary. BL corresponds to Baseline, S1 corresponds to Scenario 1, and S2 corresponds to Scenario 2.

Park (2018) reported that a TN:TP ratio of 30:1 can be considered a relevant standard for assessing nutrient limitation.

Figure 5-33 shows the ratio of 95^{th} percentile spatial distribution of Total Nitrogen to Total Phosphorous in the water column of Maketū Estuary under the Baseline, Scenario 1, and Scenario 2 respectively.

Predicted ratios of TN:TP in the western and central portion of the estuary are below 30 under Baseline and Scenario 1 runs respectively.

In Scenario 2, a TN:TP ratio of less than 20 is predicted in the central portion of the estuary.

In the area in the vicinity of the three minor catchment sources (56, 58, and 59) the ratio of TN:TP of less than 10 in Scenario 1 and less than 30 in Baseline and Scenario 2 simulation results.

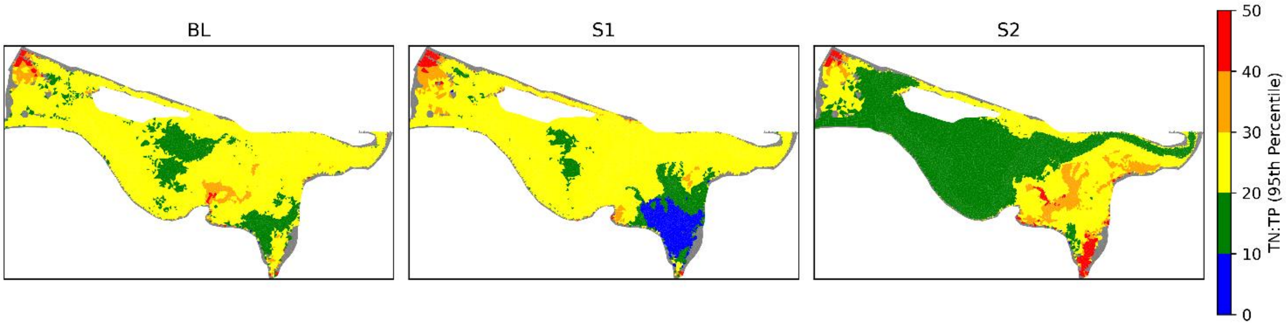

Figure 5-33 95th percentile Total Nitrogen:Total Phosphorous ratio levels in Maketū Estuary. BL corresponds to Baseline, S1 corresponds to Scenario 1, and S2 corresponds to Scenario 2.

These results indicate that achieving a TN:TP ratio of 30:1 is not feasible across the whole estuary under the scenarios considered. This would suggest that Maketū Estuary is nitrogen limited and will therefore be sensitive to increases in nitrogen levels.

Figure 5-34 shows the 95th percentile spatial distribution of Chlorophyll-a levels in the water column for the Baseline, Scenario 1, and Scenario 2 respectively.

Predicted Chlorophyll-a levels in the eastern portion of the estuary are higher than 6 µg/L in Baseline run.

No levels higher than 2 µg/l are predicted in Scenario 1 across most the estuary.

Predicted Chlorophyll-a levels between 4 µg/L and 6 µg/L are observed in the eastern region of the estuary in Scenario 2 run.

Positive relationships between nutrient loadings and chlorophyll-a concentrations are well established for many aquatic systems.

A higher chlorophyll-a concentration indicates increase in primary production. A positive feedback mechanism occurs enhancing the effect of nutrient loadings.

Similarly, reduction in nutrient loads leads to decreased primary production and lower chlorophyll-a concentration, as observed in the spatial plot of Scenario 1 in Figure 5-34.

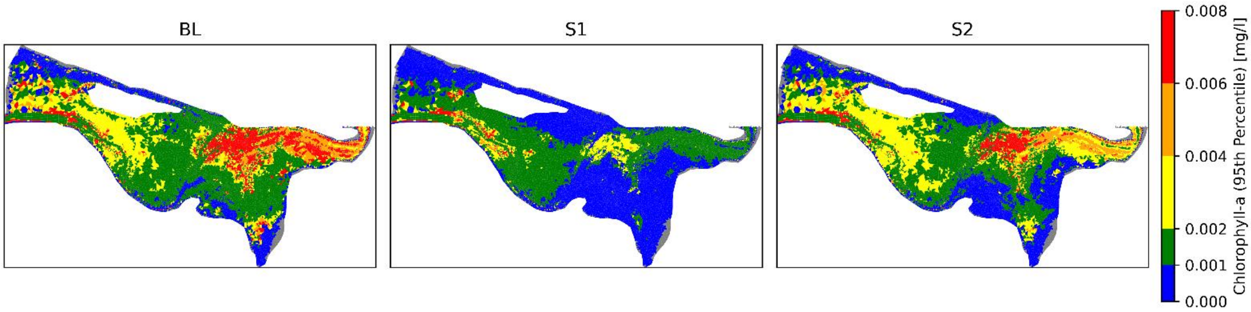

Figure 5-34 95th percentile spatial plots of Chlorophyll-a in Maketū Estuary. BL corresponds to Baseline, S1 corresponds to Scenario 1, and S2 corresponds to Scenario 2.

Figure 5-35 shows the spatial distribution of 50th percentile Macroalgae levels during summer in Maketū Estuary for Baseline, Scenario 1, and Scenario 2 results respectively.

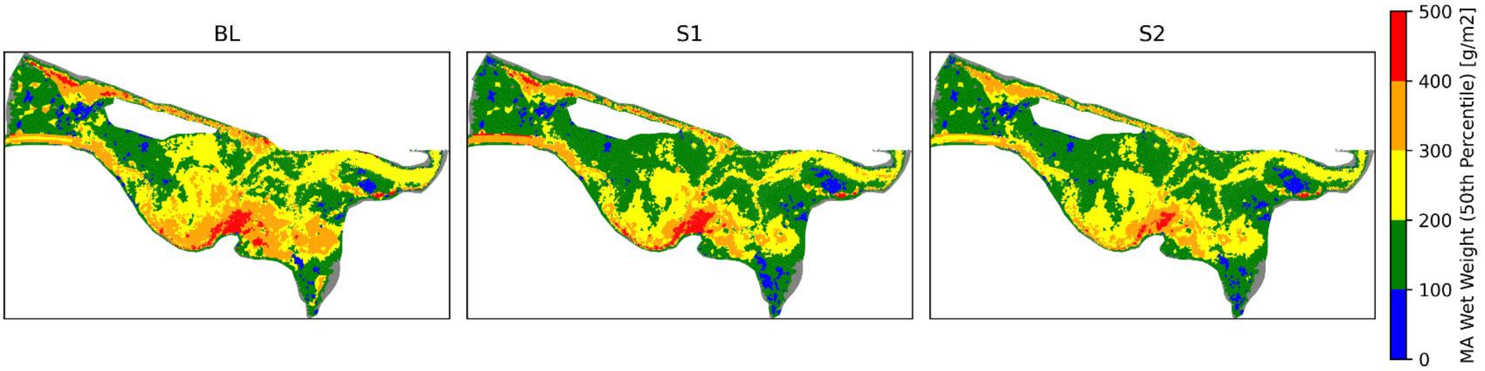

Figure 5-35 50th Percentile spatial plot of Macroalgae (gC/m2) during summer in Maketū Estuary. BL corresponds to Baseline, S1 corresponds to Scenario 1, and S2 corresponds to Scenario 2.

In Maketū Estuary, macroalgae abundance levels are predicted to be higher in central region of the estuary as compared to other regions. This region carries higher levels of nitrogen deposition (

Figure 5-28) and phosphorous deposition (Figure 5-32) in the sediment layer. It is likely that resuspension of these deposited nutrients will play a role in causing elevated macroalgae growth in the central portion of the estuary.

A reduction of macroalgae growth is observed in central, eastern, and south eastern regions of the estuary in Scenario 1 and Scenario 2 as compared to Baseline.

Model predicted that median macroalgae wet weight is between 200 and 250 g/m2 across the estuary for all the three simulation runs. This categorizes Maketū Estuary to Band C for ecological quality based on NZ Estuary Trophic Index Screen Tool 2 (Robertson 2016b).

Figure 5-36 shows the difference plots of the 95th percentile results of Scenario 1 and 2 as compared to baseline model results. The figure quantifies the difference (in percentage) in predicted macroalgae biomass in different regions of the estuary. Negative percentages indicate increase in biomass levels in the scenarios as compared to baseline levels. Positive percentages indicate decrease in biomass levels in the scenarios as compared to baseline levels.

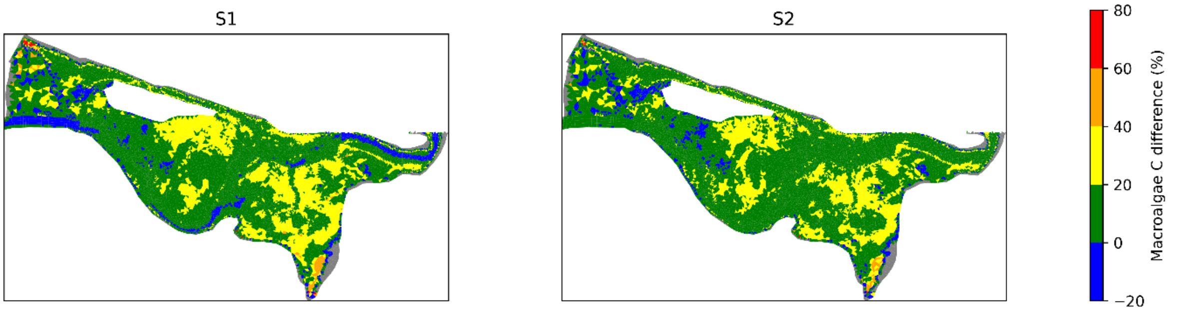

Figure 5-36 Difference plots of 95th percentile (Macroalgae) in Maketū Estuary during summer. S1 corresponds to Scenario 1 and S2 corresponds to Scenario 2.

Figure 5-37 shows the 95th percentile spatial distribution of seagrass in the water column under the Baseline, Scenario 1, and Scenario 2 respectively.

In all three runs, seagrass spatial extent is predicted to be higher in eastern region of the estuary.

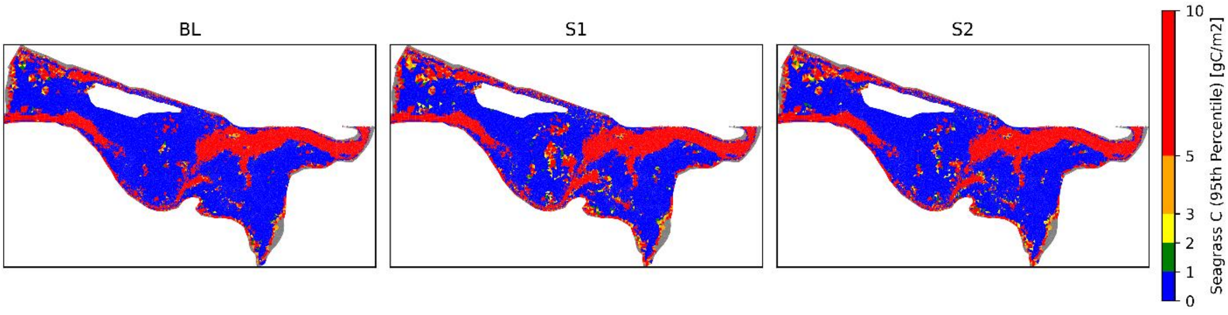

Figure 5-37 95th percentile spatial plots of seagrass distribution (gC/m^2) in Maketū Estuary. BL corresponds to Baseline, S1 corresponds to Scenario 1, and S2 corresponds to Scenario 2.

Despite the predicted reductions in nutrient levels in Scenario 1 and Scenario 2, the predicted seagrass spatial extent does not show a significant increase among the two scenarios as compared to the baseline.

These results indicate that nutrient reductions from the catchment alone are not sufficient for changes in seagrass abundance in the estuary.

Macroalgae growth and seagrass abundance are influenced by several parameters and computing regression from one parameter is not realistic.

One of the health indicators for seagrass growth is light attenuation. More light attenuation in the estuary indicates less light availability for seagrass growth to flourish.

Figure 5-38 shows the spatial plots of light attenuation (95th percentile results) in the water column under the Baseline, Scenario 1, and Scenario 2 respectively.

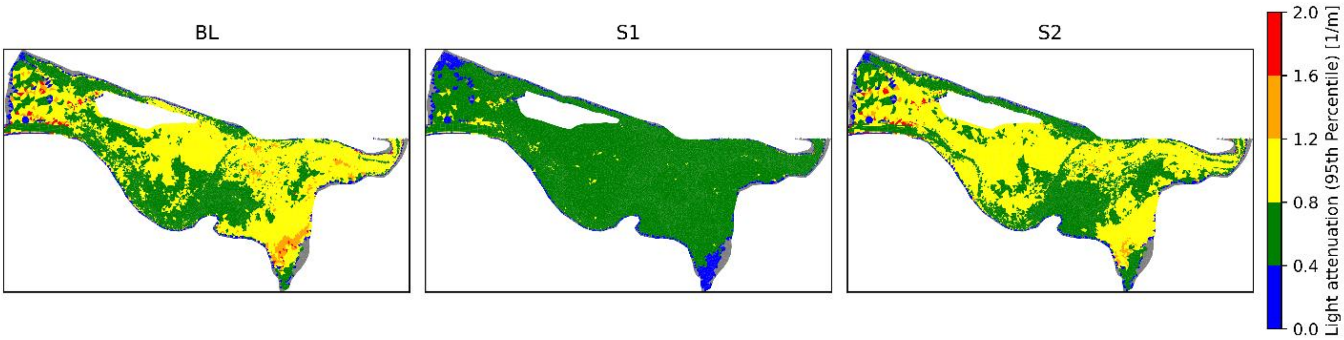

Figure 5-38 95th percentile spatial plots of light attenuation (1/m) in Maketū Estuary. BL corresponds to Baseline, S1 corresponds to Scenario 1, and S2 corresponds to Scenario 2.

In Figure 5-38, we observe that light attenuation is lower in Scenario 1 as compared to Scenario 2 across most of the estuary. This is the result of higher reductions of catchment derived nutrient and TSS loading to the estuary in Scenario 1 as compared to Scenario 2.

Another health indicator for seagrass growth is the absence of mud in the estuary. Seagrass does not grow well in muddy areas of the estuary. Figure 5-11 and Figure 5-12 indicate that the central region of the estuary is characterized by clay and silt deposition. There is minimal sand deposition observed in this area.

Another indicator for seagrass growth is the initial biomass of macroalgae and seagrass used for modelling. The initial biomass values used for macroalgae and seagrass modelling were less than 10 g C/m^2, similar to other studies (Kuusemäe 2016, Flindt 2016, and Kuusemäe 2018). However, due to similar order of initial values between macroalgae and seagrass, competition between the two could have resulted in lower seagrass growth despite reductions in nutrient loadings.

Table 5-8 Individual stressors and thresholds for seagrass recovery (adapted from Flindt 2016)

		Recovery				
Parameter (layer)	Unit	Very poor	Poor	Threshold	Good	Optimal
T_{wc}	N m^{-2}	>1	0.7-1.0	0.5-0.7	0.2-0.5	0.0-0.2
Sediment LOI	%	>10	5-10	2-5	1-2	0-1
DIN	g N l^{-1}	> 150	75-150	50-75	25-50	0-25
DIP	g P l^{-1}	>30	15-30	10-15	5-10	0-5
Resuspension	Frequency	> daily	daily	monthly	Biannual	< Biannular
Benthic light	µE m^{-2} s^{-1}	0-100	100-200	200-300	300-400	> 400
O_2 limitation	Period	3 Week^{-1}	2 Week^{-1}	Weekly	Monthly	< Monthly
Opp. Macroalgae	g C m^{-2}	>26	13	10	6	< 2
Non-opp. Macroalgae	g C m^{-2}	>26	13	10	6	< 2
Lugworm	g WW m^{-2}	>50	40	25	10	<9
Eelgrass	g C m^{-2}	< 3	< 7	< 14	< 28	> 28

Flindt (2016) presented different thresholds for seagrass recovery with respect to multiple stressors as shown in Table 5-8. The stressors include the parameters listed in the first column (except for the last row). Twc (shear stress) is a measure for the physical stress induced at the seabed due to current and waves. It will prevent seedlings from growing and potentially damage existing seagrass meadows. Sediment LOI (Loss of Ignition) is a measure of organic content in the sediment. High values of sediment LOI will impact the sediment anchoring capacity for seagrass.

As a combination of stressors including nutrient loadings, light availability, presence of sand, sediment organic enrichment, and competition from macroalgae affect seagrass growth in the estuary, restorative actions which address these stressors are recommended.

6 Summary and Conclusions

Bay of Plenty Regional Council commissioned DHI to undertake numerical modelling of Maketū Estuary. The modelling was aimed at determining acceptable levels of catchment derived nutrients, sediment and bacteria flowing into Maketū Estuary that would support a healthy environment, particularly in terms of ecological functioning and integrity that align with the values and needs of the local and wider community. In addition to baseline (representing the state of Maketū Estuary in 2014), two additional scenarios were modelled – one representing naturalised state catchment load contributions (Scenario 1) and the other representing Scenario C+M1 catchment load contributions (Scenario 2).

The final set of numerical models included a coupled hydrodynamic model, sediment transport model, bacterial fate and transport model, nutrient fate and transport model, and ecological model of macroalgae and seagrass in the estuary. Input data derived from the eWater SOURCE catchment modelling and field monitoring data were used to feed these numerical models. In addition to the Kaituna River source, three additional sources of catchment flows and loads into Maketū Estuary were used as inputs to the models.

Modelling results are summarized below -

- **Sedimentation assessment**:

  Care has to be taken when interpreting the results from sedimentation modelling, since the estuary is finding a new morphological balance since the re-diversion of the Kaituna River was completed.

  Scenario 1 is characterised by a reduction of approximately 70% of the sediment loads over 2014 compared to the Baseline Scenario. Natural state evaluations are helpful to understand what the estuarine conditions would have been prior to extensive land clearing and modification.

  Scenario 2 which includes the combined effect of land use and management practices is characterised by an increase in sediment load of approximately 20% over 2014 compared to the Baseline Scenario.

  The modelling indicates that Scenario 2 will have a small (but still undesirable) impact on predicted sedimentation rates within the estuary, while Scenario 1 produces a significant reduction in the sedimentation rates within the harbour.

- **Bacterial assessment**:

  In Baseline conditions, catchment inflows of E.cocci and F.coli into Maketū Estuary amounted to 7.74×10^{14} cfu/yr, and 1.1×10^{15} MPN/yr respectively.

  In Scenario 1, 4.8×10^{14} cfu/yr of E.cocci loads and 6.6×10^{14} MPN/yr of F.coli loads into Maketū Estuary was observed.

  In Scenario 2, 6.7×10^{14} cfu/yr of E.cocci loads and 9.4×10^{14} MPN/yr of F.coli loads into Maketū Estuary was observed.

  In all three scenarios, Kaituna River contributed about 90% or more of E.cocci and F.coli loads from the catchment to Maketū Estuary.

  Analysis of the 2014 E.cocci inflows with respect to meeting microbiological water quality guidelines for primary contact recreation/bathing based on an E.cocci concentration showed that -

- In all three simulations, Source 59 inflows met the guideline value 100% of the annual period.
- Kaituna River inflows met the guideline value for more than 95% of the annual period in all three simulations.
- In Scenario 1, Sources 56 and 58 meet the guideline for 85% of the annual period.
- In Scenario 2, Sources 56 and 58 meet the guideline at least 80% of the annual period.

Seasonal investigation of E.cocci loads to Maketū Estuary under the Baseline scenario showed that, on average, the guideline was exceeded for 18% of Winter, 10% of Spring, 17% of Summer, and 15% of Autumn.

For Scenario 1, the guideline was exceeded for about 9% of Winter, 2% of Spring, 6% of Summer, and 8% of Autumn.

For Scenario 2, the guideline was exceeded for about 12% of Winter, 4% of Spring, 9% of Summer, and 11% of Autumn.

In Maketū estuary, the predicted median E.cocci levels across the estuary meet the guideline value of 280 cfu/100 ml in all three scenarios.

The predicted 95th percentile E.cocci levels meet the guideline value across most of the estuary in all three scenarios.

Only near the sources in the south east region of the estuary in Baseline and Scenario 2 simulations, E.cocci levels do not meet guidelines value.

In all three simulations, we observe that the E.cocci levels meet the guideline value for more than 95% of annual period for most of the estuary.

In Baseline, in the spatial area near the three sources (56, 58, and 59) in the south eastern region of the estuary, we observe E.cocci levels exceed the guideline value for more than 15% of annual period.

This part of the estuary is characterized by shallower water depths. Shallower water depths mean less dilution as well as less flushing due to subsequent dilution. This leads to more E.cocci loads retained near the sources.

The order observed for meeting guidelines annually is Scenario 1 > Scenario 2 > Baseline.

In Scenario 1, we observe that the E.cocci levels meet the guideline value for 99% of spring, summer, and autumn periods across the estuary. In winter, we observe E.cocci levels exceed the guideline value for less than 5% of the season across most of the estuary.

In Baseline and Scenario 2, we observe that the E.cocci levels meet the guideline value for 99% of spring and summer periods across the estuary.

In winter, we observe that the E.cocci levels exceed the guideline value for more than 5% of the season in western, central, and south eastern regions of the estuary.

We also observe that spatial areas downstream of Kaituna River inflow show E.cocci levels exceed the guideline value for more than 5% of time in winter season in only Baseline and Scenario 2 runs.

The order observed for meeting guidelines seasonally is Spring > Summer > Autumn > Winter.

Based on analysis at 95th percentile level, model results predict that a 20.39% reduction of baseline catchment loads is required for E.cocci levels across the whole of the Maketu estuary to meet the guideline value.

Analysis of the 2014 F.coli inflows with respect to meeting microbiological water quality guidelines for shellfish gathering based on F.coli concentration show that –

- In all scenarios, Source 59 inflows met the guideline value for more than 98% of the annual period in all three simulations.
- Kaituna River inflows met the guideline value for more than 95% of the annual period in all three simulations.
- In Scenario 1, Sources 56 and 58 meet the guideline for 30% of the annual period.
- In Scenario 2, Sources 56 and 58 meet the guideline at least 20% or more of the annual period.

Analysis of the 2014 inflows with respect to meeting microbiological water quality guidelines for shellfish gathering showed that that catchment sources 56 and 58 breach the guideline value more than 60% of the annual time period in all three runs.

Seasonal investigation of F.coli loads to Maketū Estuary under the Baseline scenario showed that, on average, the guideline was exceeded for 60% of Winter, 46% of Spring, 47% of Summer, and 45% of Autumn.

For Scenario 1, the guideline was exceeded for about 49% of Winter, 33% of Spring, 38% of Summer, and 37% of Autumn.

For Scenario 2, the guideline was exceeded for about 55% of Winter, 38% of Spring, 42% of Summer, and 41% of Autumn.

F.coli Loads from Kaituna River exceed the guideline value for about 20% of the annual time period for Baseline and Scenario 2 simulation.

In Maketū Estuary, the predicted 50th percentile F.coli levels below the guideline value of 14 MPN/100ml are observed across most of the estuary in all three scenarios.

In Scenario 1, we observe F.coli levels meet the guideline value for more than 80% of annual period for most of the estuary.

In Baseline and Scenario 2, we observe F.coli meet the guideline value for more than 70% of annual period for most of the estuary.

In all three scenarios, in the spatial area near the three sources (56, 58, and 59) in the south eastern region of the estuary, we observe F.coli levels exceed the guideline value for more than 40% of annual period.

The order observed for meeting guidelines annually is Scenario 1 > Scenario 2 > Baseline.

With respect to seasonal analysis, as shown in Figure 5 25, in Scenario 1, we observe that most of the estuary meets the guideline value for summer period across the estuary. In contrast, during winter, F.coli levels exceed the guideline value for more than 20% of the season across the estuary.

In Baseline and Scenario 2, we observe F.coli exceed the guideline value for less than 20% of spring, summer, and autumn seasons for most of the estuary. In contrast, during winter, F.coli levels exceed the guideline value for more than 30% of the season across the estuary.

In all three scenarios, in each of the four seasons, in the spatial area near the three sources (56, 58, and 59) in the south eastern region of the estuary, the area of exceedance is lower in Scenario 1 as compared to Scenario 2 and Baseline.

This part of the estuary is characterized by shallower water depths. Shallower water depths mean less dilution as well as less flushing due to subsequent dilution. This leads to higher F.coli levels near the sources.

Downstream of the Kaituna River, F.coli levels exceed the guideline value for less than 20% of time during summer, autumn, and spring, and more than 40% of time in winter in all three runs.

The order observed for meeting guidelines seasonally is Summer > Spring > Autumn > Winter.

Based on analysis at 50th percentile level, model results predict that a 38.87% reduction of baseline catchment loads is required for F.coli levels across the whole Maketu estuary to meet the guideline value.

- **Nutrient and ecological assessment**:

  For the Baseline scenario, Total Nitrogen and Total Phosphorous inflows from the four sources into Maketū Estuary amounted to 1140 tonnes/year and 49.1 tonnes/year respectively.

  In Scenario 1, 366 tonnes/year of TN loads and 24.2 tonnes/year of TP loads into Maketū Estuary were observed.

  In Scenario 2, 699 tonnes/year of TN loads and 41.5 tonnes/year of TP loads into Maketū Estuary were observed.

  The Kaituna River contributed between 91% and 99% of the annual loads of Total Nitrogen, and 94% to 96% of the annual loads of Total Phosphorous to Maketū Estuary in all three simulation runs.

  TN loads to Maketū Estuary in winter loads ranged from 46-54% of the total annual load in all three scenario runs, summer TN loads ranged from 11-13% of the total annual load, spring TN loads ranged from 19-21% of the total annual load, and autumn TN loads ranged from 16-20% of the total annual loads in all three scenario runs.

  TN loads from the Kaituna River formed about 99% of the total loads in each of the four seasons for Scenario 1 run, and about 90-92% of the total loads in each of the four seasons for Baseline and Scenario 2 runs respectively.

  TP loads to Maketū Estuary in winter ranged from 37-42% of the total annual load, summer TP loads ranged from 16-18% of the total annual load, spring TP loads ranged from 19-21% of the total annual load, autumn TP loads ranged from 16-20% of the total annual loads in all three scenario runs.

  Total Phosphorous loads from the Kaituna River formed about 96% of the total loads in each of the four seasons for Scenario1 run, about 92-96% of the total loads in each of the four seasons for Baseline run, and about 95-97% of the total loads in each of the four seasons for Scenario 2 run respectively.

As per the recommended guidelines for macroalgal-dominated estuarine systems , potential TN concentration in the estuary should be less than 0.055 mg/l for the estuary to be categorize to Trophic State Band A (near reference), between 0.055 mg/l and 0.18 mg/l for the estuary to be categorized to Trophic State Band B (slightly impacted), between 0.18 mg/l and 0.35 mg/l for the estuary to be categorized to Trophic State Band C (moderately impacted), and above 0.35 mg/l for the estuary to be categorized to Trophic State Band D (heavily impacted).

In Baseline, the predicted median concentration of TN is above 0.35 mg/l across the estuary. This categorizes Maketū Estuary to Trophic State Band D (heavily impacted).

In Scenario 1, the predicted median concentration of TN is between 0.055 mg/l and 0.18 mg/l for most of the estuary. This categorizes Maketū Estuary to Trophic State Band B (slightly impacted).

In Scenario 2, the predicted median concentration of TN is above 0.35 mg/l in most of the estuary. This categorizes Maketū Estuary to Trophic State Band D (heavily impacted).

Based on the model results, about 52% or 64% reduction in Baseline TN catchment loads (median) is required for Maketū Estuary to achieve max-Band C or mid-Band C Trophic State respectively. About 75% or 84% reduction in Baseline TN catchment loads (median) is required for Maketū Estuary to achieve max-Band B or mid-Band B Trophic State respectively.

The total mass of Total Nitrogen deposited across the estuary is predicted to be 59.7 tonnes/year, 43 tonnes/year, and 59.3 tonnes/year for the Baseline, Scenario 1, and Scenario 2 simulations respectively.

In Maketū Estuary, predicted levels of Total Phosphorous in the south eastern region of the estuary are higher than 0.16 mg/l for the Baseline and Scenario 2 runs respectively. This is the area in the vicinity of the sources. No levels higher than 0.12 mg/l are observed in Scenario 1 across the estuary.

The amount of Nitrogen efflux (from the sediment to water column) is predicted to be 17 tonnes/year, 11 tonnes/year, and 15 tonnes/year for the Baseline, Scenario 1, and Scenario 2 simulations respectively.

In Scenario 1 and Scenario 2, the amount of nitrogen efflux from the sediment to water column is predicted to be more than 25% of the total load to the estuary.

Based on the analysis of the 95th percentile spatial distribution of TP in the water column of Maketū Estuary, following were observed -

- Predicted levels of TP are less than 0.04 mg/l across most of the estuary in Scenario 1 whereas levels are above 0.04 mg/l across most of the estuary in Scenario 2.
- Predicted levels of TP in the south eastern region of the estuary are higher than 0.16 mg/l for the Baseline and Scenario 2 runs respectively. This is the area in the vicinity of the sources.

The total mass of Total Phosphorous deposited across the estuary is predicted to be 7.7 tonnes, 5.8 tonnes, and 7.5 tonnes for the Baseline, Scenario 1, and Scenario 2 simulations respectively.

In all three runs, deposition of more than 4 gP/m^2 is predicted to occur predominantly in the central portion of the estuary. Less than 2 gP/m^2 of deposition is predicted to occur in eastern portion of the estuary in all three runs.

In Maketū Estuary, predicted ratios of TN:TP in the western and central portion of the estuary are below 30 under Baseline and Scenario 1 runs respectively. In Scenario 2, ratio of less than 20 is predicted in the central portion of the estuary.

In the estuary, model results indicate that achieving a TN:TP ratio of 30:1 (relevant standard for assessing nutrient limitation) is not feasible for the given catchment loadings in all the three scenario runs. It can be inferred here that Maketū Estuary is Nitrogen limited and therefore sensitive to increases in nitrogen levels.

In the estuary, 95th percentile spatial distribution of Chlorophyll-a levels in the water column shows that predicted levels are higher than 8 µg/L in Baseline and Scenario 2 simulations in the eastern region of the estuary. Levels lower than 2 µg/l are observed in Scenario 1 across the estuary.

Model predicted that median macroalgae wet weight is between 200 and 250 g/m^2 across the estuary for all the three simulation runs. This categorizes Maketū Estuary to Band C for ecological quality based on NZ Estuary Trophic Index Screen Tool 2.

In Maketū Estuary, macroalgae abundance levels are predicted to be higher in central region of the estuary. This portion carries higher levels of nitrogen and phosphorous deposition in the sediment layer. Resuspension of these deposited nutrients could play a role in causing elevated macroalgae growth in the central portion of the estuary.

In Maketū estuary, in all three runs, seagrass spatial extent is predicted to be higher in eastern portion as compared to the rest of the estuary.

Although seagrass spatial extent does not show significant difference under Scenario 1 and Scenario 2 as compared to the Baseline results, the abundance levels of seagrass are predicted to increase in both Scenario 1 and Scenario 2 as compared to the Baseline simulation results.

Results indicate that nutrient reductions from the catchment alone are not sufficient for changes in seagrass spatial extent in the estuary. A combination of factors including nutrient loadings, light availability, presence of sand, and competition from macroalgae growth affect the growth of seagrass in the estuary.

One of the health indicators for seagrass growth is light attenuation. More light attenuation in the estuary indicates less light availability for seagrass growth to flourish.

Model predicts that light attenuation is lower in Scenario 1 as compared to Scenario 2 across most of the estuary. This could be due to higher reductions of catchment derived nutrient and TSS loading to the estuary in Scenario 1 as compared to Scenario 2.

Another health indicator for seagrass growth is the presence of sand in the estuary. Seagrass does not grow well in muddy areas of the estuary. Sedimentation results indicate that the central region of the estuary is characterized by clay and silt deposition. There is minimal sand deposition observed in this area

In conclusion, for bacterial assessment the levels of E.cocci and F.coli observed in the estuary are directly proportional to the catchment derived loads. Based on model results, key recommendations include –

- For recreational health, mitigation to be directed only to the area downstream of near the three sources in the south eastern region of the estuary.
- Shellfish collection is not recommended during winter.
- Based on median value results, areas for shellfish collection could be all across the estuary except near the sources

Based on nutrient and ecological assessment, we learnt that complex processes are at play affecting nitrogen and phosphorous availability for primary production, deposition to sediment layers, and uptake for macroalgae and seagrass growth in the estuary.

Results indicate that nutrient reductions from the catchment alone are not sufficient for changes in seagrass abundance in the estuary. As a combination of stressors including nutrient loadings, light availability, presence of sand, and competition from macroalgae growth affect the growth of seagrass in the estuary, restorative actions which address these stressors are recommended.

Modelling assessments presented in this report quantified the hydrodynamics, sediment, bacterial, nutrient, and ecological conditions of Maketū Estuary. Based on the model results, target levels of loading have been determined for E.cocci, F.coli, Nitrogen, and Macroalgae that would result in a healthy and productive ecosystem in Maketū Estuary.

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