Mangawhai catchment contaminant loading and estuary impacts

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Climate, Freshwater & Ocean Science

Prepared by:
Sandy Elliott
Annette Semadeni-Davies
David Plew

For any information regarding this report please contact:

Sandy Elliott
Principal Scientist
Catchment Processes
+64 7 859 1839
sandy.elliott@niwa.co.nz

National Institute of Water & Atmospheric Research Ltd
PO Box 11115
Hamilton 3251

Phone +64 7 856 7026

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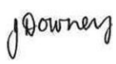
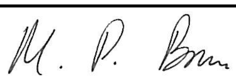
	Formatting checked by:	Jo Downey
	Approved for release by:	Michael Bruce

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Background

This report presents a screening-level modelling assessment of nutrient and sediment loads to Mangawhai Estuary and the associated eutrophication and sediment deposition risks. The study was performed as a part of Stage 2 of the Sustainable Mangawhai Project, which has the goal of providing an appraisal of the state of the harbour and threats to its future. The project was funded through Mangawhai Matters Inc. (MMI).

Methods

Nutrient, sediment and *E. coli* load to the estuary were estimated under current and future conditions, as explained below. Nitrogen loads were used to determine risks of estuary eutrophication under these loadings, while an approximate estuary sedimentation model was used to estimate estuary sedimentation rates.

Mean annual total nitrogen (TN), total phosphorus (TP) and *E. coli* loads to the estuary were determined using the catchment model CLUES (Catchment Land Use for Environmental Sustainability). CLUES was set up for the Mangawhai catchment using model inputs and parameters established previously for Northland, but with some modifications such as extending the catchment to include inputs from the estuary fringes (areas near the estuary that are no associated with a stream) so that the full estuary catchment was modelled. Future changes in nutrient loading from disposal of sewage effluent in the catchment were determined from existing assessments, and changes in loading associated with future land use change were assessed in broad terms considering typical losses from land uses.

Mean annual sediment loads were assessed with the erosion model NZSYE (New Zealand Sediment Yield Estimator). The model accounts for variation in land use, slope, rain and geology. The increase in sediment loading under future climate change were assessed for temperature increase increments. The increments can be related to different future time horizons and climate emissions scenarios. This effect of temperature change was determined using estimate of rainfall erosivity based on increased storm depth and intensity, which can be related to temperature increases based on the HIRDS (High Intensity Rainfall Distribution System) model. Predictions were made for temperature increases up to 3 °C (which represents increases from a high-emissions scenario in at the end of this century SSP3-7.0 (Shared Socioeconomic Pathway) scenario). The effect of future urban earthworks on sediment loss to the estuary was estimated based on anticipated areas of urban development (provided by MMI) and expected sediment yields (load per unit source area) for urban earthworks that have good erosion controls. Eutrophication risks for macroalgae (sea lettuce or seaweed) and phytoplankton (small suspended algae) were assessed using the Estuary Trophic Index model. That model uses nitrogen loading to the estuary, inflow rates, and estuary flushing characteristics to determine the potential for macroalgal and phytoplankton abundance, which was then categorised in a terms of grading bands (A-D).

Sedimentation risks were determined using sediment loads from the catchment and a simple sediment deposition model. The estuary was split into four sub-estuaries and the catchment leading directly to each sub-estuary (estuary subcatchments) were determined. Sediment loads from each subcatchment were calculated from the erosion model. The subcatchment loads were then distributed to sub-estuaries according to specified distribution proportions, and the total load to each sub-estuary was spread over the sub-estuary area to arrive at a sediment deposition depth.

This gives a preliminary indication of sedimentation risks but does not account for sediment remobilization and re-distribution following deposition of storm-related sediment loading. Two sets of distribution proportions were considered – a low scenario and a high scenario – to reflect uncertainty in the proportions.

Key results

Nutrients and eutrophication

Nutrient loads to the estuary for the current land use were estimated to be 55.4 t/year for TN and 5.8 t/year for TP. There is currently no load from the sewage treatment plant, because disposal of treated effluent is outside the catchment. Comparison of measured concentrations and simulated concentrations (using an approximate method) showed reasonable agreement. The load from horticulture/viticulture in the catchment was likely over-estimated.

The risk of macroalgal growth was predicted to be small, with TN concentrations indicating an A grading band in relation to macroalgae. For phytoplankton the predicted band was B, although risks of associated impacts such as de-oxygenation and light reduction were considered to be small, given the nature of the estuary. Phosphorus loads are not expected to have a eutrophication impact for this estuary, which is typical for well-flushed estuaries.

These eutrophication risks are not expected to increase in the future. Possible future disposal of treated effluent to land and a wetland in the catchment would only increase loading to a small degree (2.7%). Loads from future urban or lifestyle blocks are expected to be comparable to or less than loads from the land uses that would displace. Potentially, widespread introduction of nutrient-intensive horticulture or market gardens would increase eutrophication risks, but such a scenario is unlikely given the characteristics of the catchment and pressure for large-lot residential development.

Sediment load and deposition

There was moderate to low predicted sediment yield for the overall catchment (42.7 t/km^2/year) reflecting the slopes, surface rock types, and land cover in the catchment. This yield is consistent with measured yields in comparable catchments in Auckland. While there are steep areas in the Brynderwyn hills, they are covered with mostly native vegetation and have greywacke geology, so there is low erosion risk for those areas. There is little risk of landslides in the catchment, because slopes on pasture areas are almost all less than 24 degrees, a threshold for landslides for the types of geology in the catchment. This is consistent with aerial imagery showing negligible landsliding following Cyclone Gabrielle. There is considerable variation of predicted yields across pasture areas in the catchment, with yields up to 250-450 t/km^2/year in small areas of steeper pasture, and low yields (about 10 t/km^2/year) in in flat areas. About half the load comes from the Southern Arm subcatchment, and half from the Tara Arm subcatchment.

Deposition rates based on these erosion rates would amount to an average deposition depth of 0.59 mm/year if the entire input sediment load were spread out evenly over the non-channel parts of the entire estuary. The deposition depth in Back Bay would be about 1.2 mm/year for a high-deposition scenario (50% to 75% of the incoming sediment from the contributing subcatchments being deposited in Back Bay, depending on the subcatchment), which is below ecological thresholds of 2 mm/year.

This depth is uncertain due to uncertainty in the proportions of catchment sediment depositing in the area. Importantly, this estimate does not account for erosion and redistribution of sediment already in the estuary. Deposition rates in some parts of the sub-estuary would likely be larger than the sub-estuary average, but that was not assessed in this study.

Catchment erosion rates are predicted to increase by a factor of 1.63 (63% increase) for a temperature increase of 3°C. Such an increase is projected to occur for the high-emissions SSP3-7.0 climate scenario around the end of the century. This would increase the deposition value to about 2 mm/year in Back Bay for the high-deposition scenario. There will be less erosion and associated deposition for smaller temperature increases, corresponding to lower-emissions scenarios or earlier timeframes.

Urbanisation was predicted to have only a minor impact on deposition rates in the estuary (2.8% or less increase). This results from the fairly small areas of earthworks compared to the total catchment area, and the fairly low slopes of areas that are expected to be subject to earthworks. This assumes that earthworks have a high standard of erosion controls, and that earthworks associated with development are spread fairly evenly over a 10-year period.

Future work

There is considerable uncertainty regarding sediment deposition rates. Additional modelling and measurements of estuary sediment processes would provide additional information to assess sediment movement patterns, sediment accumulation rates, and sediment sources responsible for deposition. This could involve developing a dynamic spatial catchment model and an estuary hydraulics and sediment transport model, along with measurements of sediment deposition rates and sediment provenance. However, this would involve considerable extra investment.

1 Background and introduction

Mangawhai Matters Inc. (MMI) initiated the Sustainable Mangawhai Project in recognition of the value of the environmental, cultural, and community services provided by Mangawhai Harbour. MMI commissioned a Stage One study and report (Mangawhai Matters Inc. 2023) to provide an appraisal of the state of the harbour and threats to its future. One of the issues identified in that report was water quality in the Harbour.

The Sustainable Mangawhai Project is moving forward to a second phase to provide more information. As part of this second phase, NIWA was commissioned by MMI to undertake a screening-level assessment of catchment contaminant loading and associated risks for estuary sedimentation and eutrophication, which is the subject of this report.

The project assessed current catchment contaminant mean annual loading and associated risks for estuary sedimentation and eutrophication. The assessment was based on existing catchment models and simplified methods for assessing catchment load and estuarine risks. The aim was to provide a screening-level assessment rather than a comprehensive or detailed modelling analysis.

The following tasks were included in the project scope (further details are provided later in the report):

1. Run the CLUES (Catchment Land Use for Environmental Sustainability catchment model for nutrients — total phosphorus (TP) and total nitrogen (TN) — and *E. coli*, providing adjustments where considered appropriate to take local factors into account (e.g., the nature of the rural land use). This was based on CLUES calibration for Northland and a national erosion model developed for Ministry for the Environment (MfE). The original intention was to run the erosion component of CLUES as well, but we instead ran the NZSYE model, which is of a similar nature to CLUES but runs at a finer spatial resolution and is better suited for erosion estimation.

2. Run the Estuarine Trophic Index tool to estimate potential eutrophication, which provides an estuary-average risk of eutrophication.

3. Conduct simple sedimentation calculations to assess potential mean annual sedimentation risk for key parts of the estuary.

4. Identify, at an indicative level, the potential for intensification of land use, urbanisation, and climate change to alter eutrophication and sedimentation.

5. Critically evaluate the above information to assess potential eutrophication and sedimentation risks.

6. Prepare a brief report summarising the methods and outputs of the project.

7. Provide a web-accessible map of contaminant sources and contextual information such as topography and land use.

The catchment boundary and key topographic information is shown in Figure 1-1.

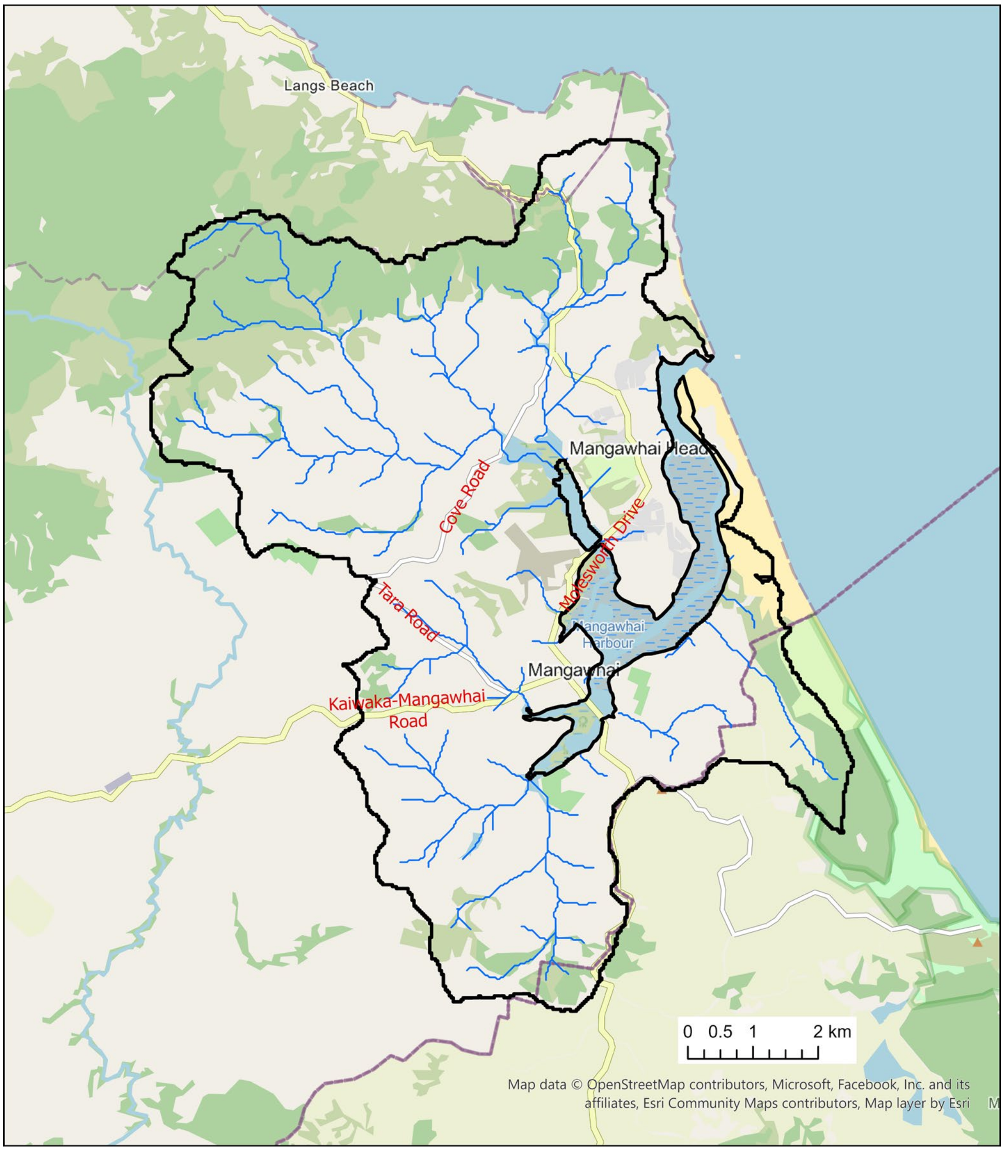

Figure 1-1: Mangawhai Estuary and catchment boundary.

2 Methods

2.1 Catchment characteristics

The models described later use several spatial layers as input data. Key layers are presented below and are discussed further in the context of model results later in the report.

2.1.1 Drainage network and estuary representation

The Mangawhai Harbour catchment has an area of around 70.2 km^2. We used the River Environments Classification (REC, version 2.5) drainage network to represent catchment drainage in the models (Snelder and Biggs 2002; Snelder et al. 2010) with the addition of coastal fringe subcatchments we created for a project undertaken for the Ministry for the Environment (Semadeni-Davies et al. 2021a). The fringe subcatchments account for the areas between the boundary of the REC network and the coast, these areas are an artefact of the spatial resolution used to derive the REC network.

The estuary has been split into six sections for reporting; these are the Tara and Southern Arms, Back Bay, Mid and Lower Estuary and the estuary Mouth. The sections and their upstream catchment areas are mapped in Figure 2-1. The catchment area draining to each section is given in Table 2-1 along with land use areas.

The boundary of the estuary in the upper reaches is based on REC subcatchments with fringing subcatchments as determined for the Ministry for the Environment work, but with some adjustments along the spit.

Table 2-1: Land use area (km^2) summary for the Mangawhai Harbour Catchment split by estuary compartment. The percentage upstream land cover for each estuary compartment is given in parentheses. Note that areas are rounded so the totals may not match the sum of the individual values exactly.

Estuary compartment	Herbaceous				Forest and scrub	Urban	Other land uses	Total
	Dairy	Sheep and Beef	Deer and other animals	Crops and horticulture				
Southern Arm	6.5 (33%)	6.4 (32%)	2.5 (12%)	0.3 (2%)	3.4 (17%)	0.3 (2%)	0.5 (2%)	19.9 (28%)
Tara Arm	5.5 (15%)	9.1 (25%)	4.1 (11%)	1 (3%)	14.1 (39%)	1.1 (3%)	1 (3%)	35.8 (51%)
Back Bay	0 (0%)	0.7(22%)	0.6 (18%)	0.1 (2%)	0.6 (19%)	1.2 (36%)	0.1 (4%)	3.4 (5%)
Mid Estuary	2.0 (25%)	2.9 (37%)	0.5 (6%)	0.3 (4%)	1.5 (19%)	0.2 (3%)	0.6 (7%)	8.0 (11%)
Lower Estuary	0 (0%)	0.1 (7%)	0 (0%)	0 (0%)	0.1 (7%)	0.6 (36%)	0.9 (50%)	1.5 (2%)
Mouth	0 (0%)	0.1 (4%)	0 (0%)	0 (0%)	0.4 (27%)	0.9 (59%)	0.2 (10%)	1.6 (2%)
Total catchment	14.0 (20%)	19.2 (27%)	7.6 (11%)	1.6 (2%)	20.2 (29%)	4.4 (6%)	3.1 (4%)	70.2 (100%)

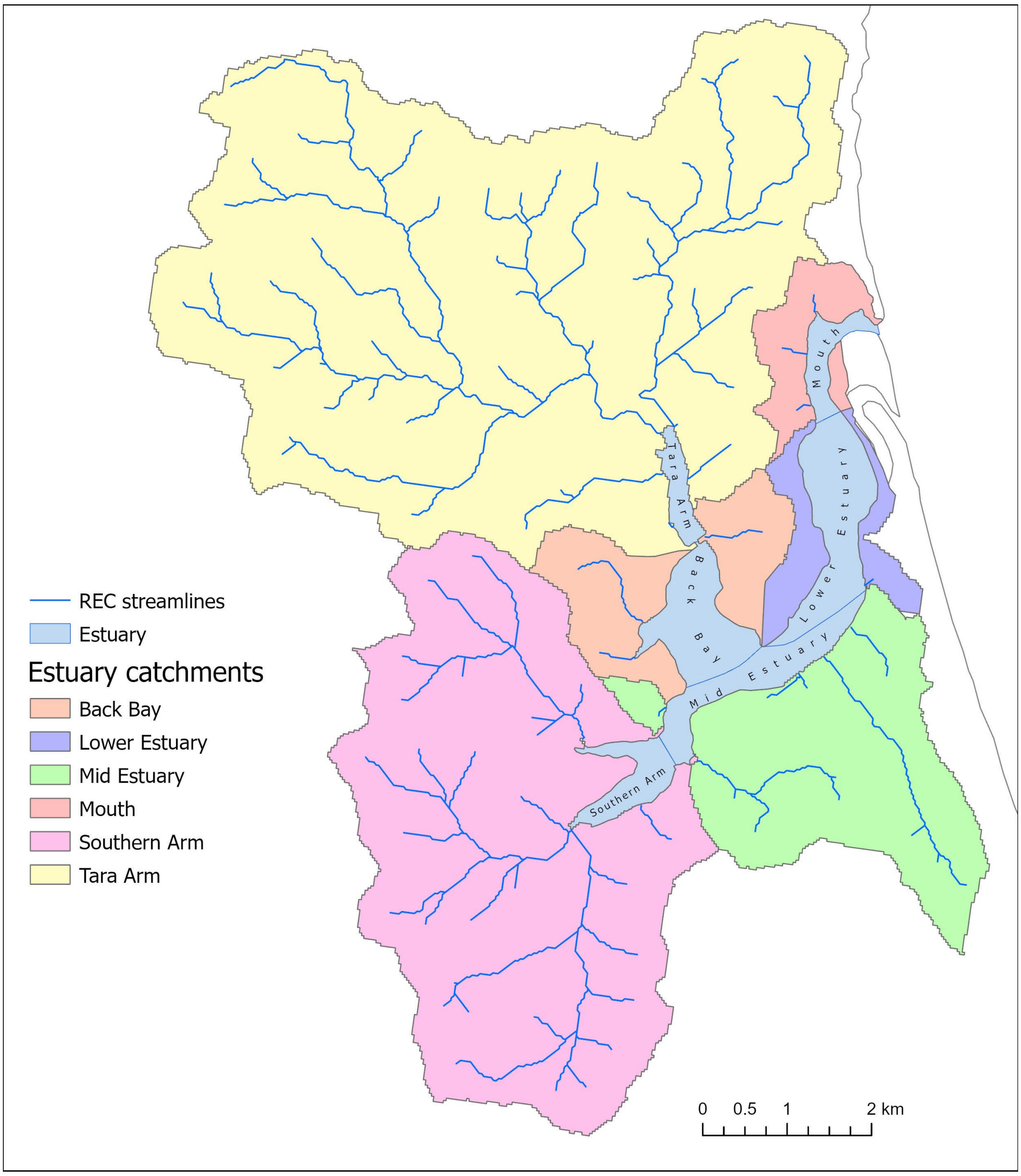

Figure 2-1: Mangawhai Harbour Catchment showing the estuary compartments, their upstream catchment areas and REC streamlines. Estuary fringes are included in the catchment areas.

2.1.2 Current land use

The current land cover layer for both models was derived from LCDB5[1,2] (Land Cover Database) and has the nominal year 2018. The LCDB5 land cover classes have been reclassified for the models nationally as part of model development (Elliott et al. 2016). CLUES has six pastoral land use classes (dairy, sheep and beef lowland intensive, hill and high country, deer, and other animals), which were derived from the LCDB grassland land covers using additional data from AgriBase[3] (reference year 2017), Department of Conservation (DOC estate) and Land Information New Zealand (LINZ). The NZSYE erosion model has three land cover classes: herbaceous (i.e., pasture, tussock, grassland and crops); wooded (native and exotic forest and scrub); and other (all remaining land covers excluding

[1] Erosion and sediment control guide for land disturbing activities in the Auckland region - Knowledge Auckland
[2] https://lris.scinfo.org.nz/layer/104400-lcdb-v50-land-cover-database-version-50-mainland-new-zealand/
[3] https://www.asurequality.com/services/agribase/

open water and urban). Land use in the catchment is summarised in Table 2-1 (above) and mapped in Figure 2-2. Note that the catchment is undergoing rapid development, and AgriBase can lag development, so the land use assessed for 2018 is likely to under-represent recent land use changes (e.g., Mangawhai Central development is not included, and conversion of operating farms into lifestyle blocks).

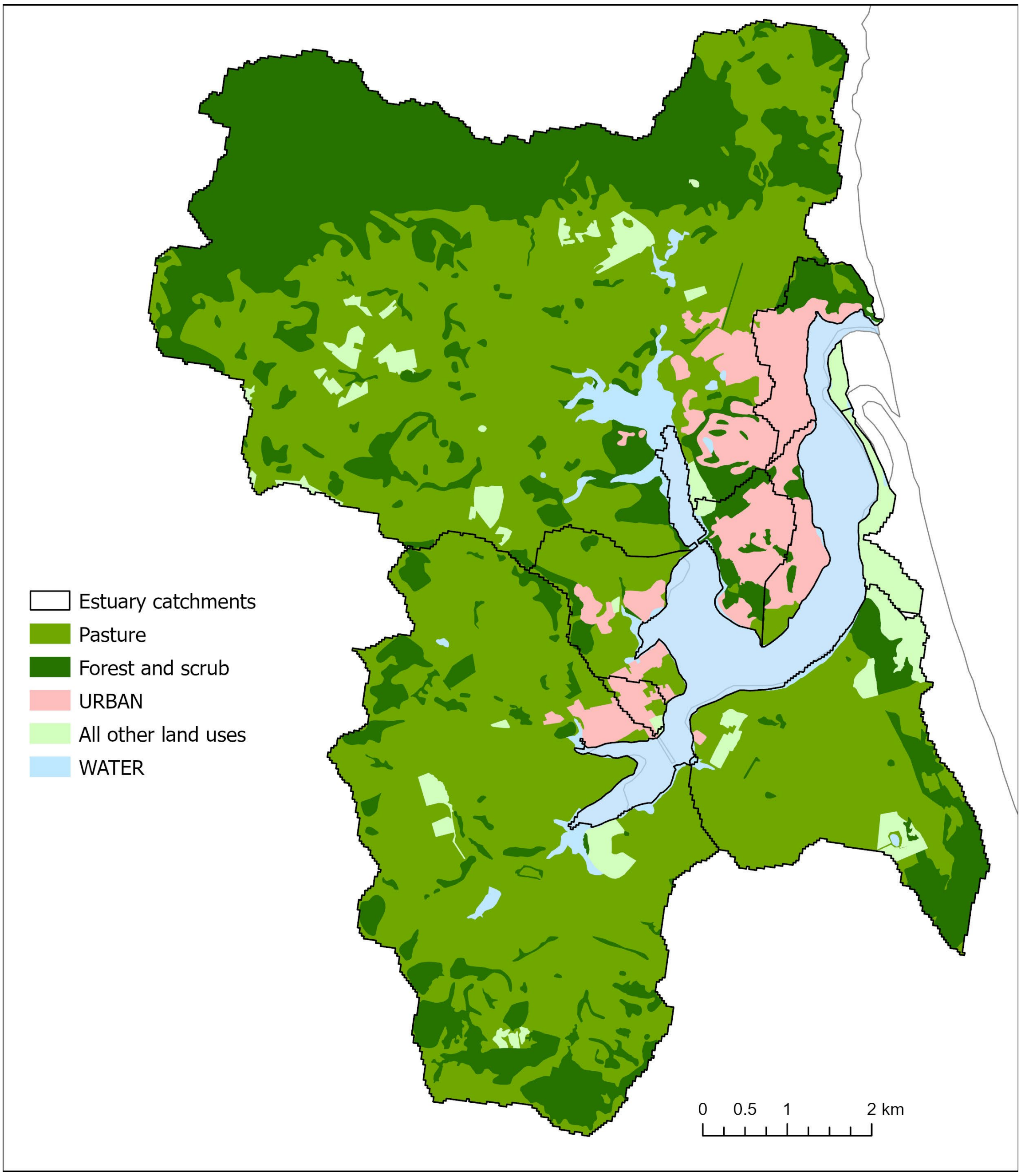

Figure 2-2: Land use distribution in the catchment.

2.1.3 Slope

The distribution of slope in the catchment, from the LINZ 8 m DEM (Digital Elevation Model), is shown in Figure 2-3. This is relevant to TP generation and to erosion. Slopes were averaged to a 100m grid for the erosion modelling.

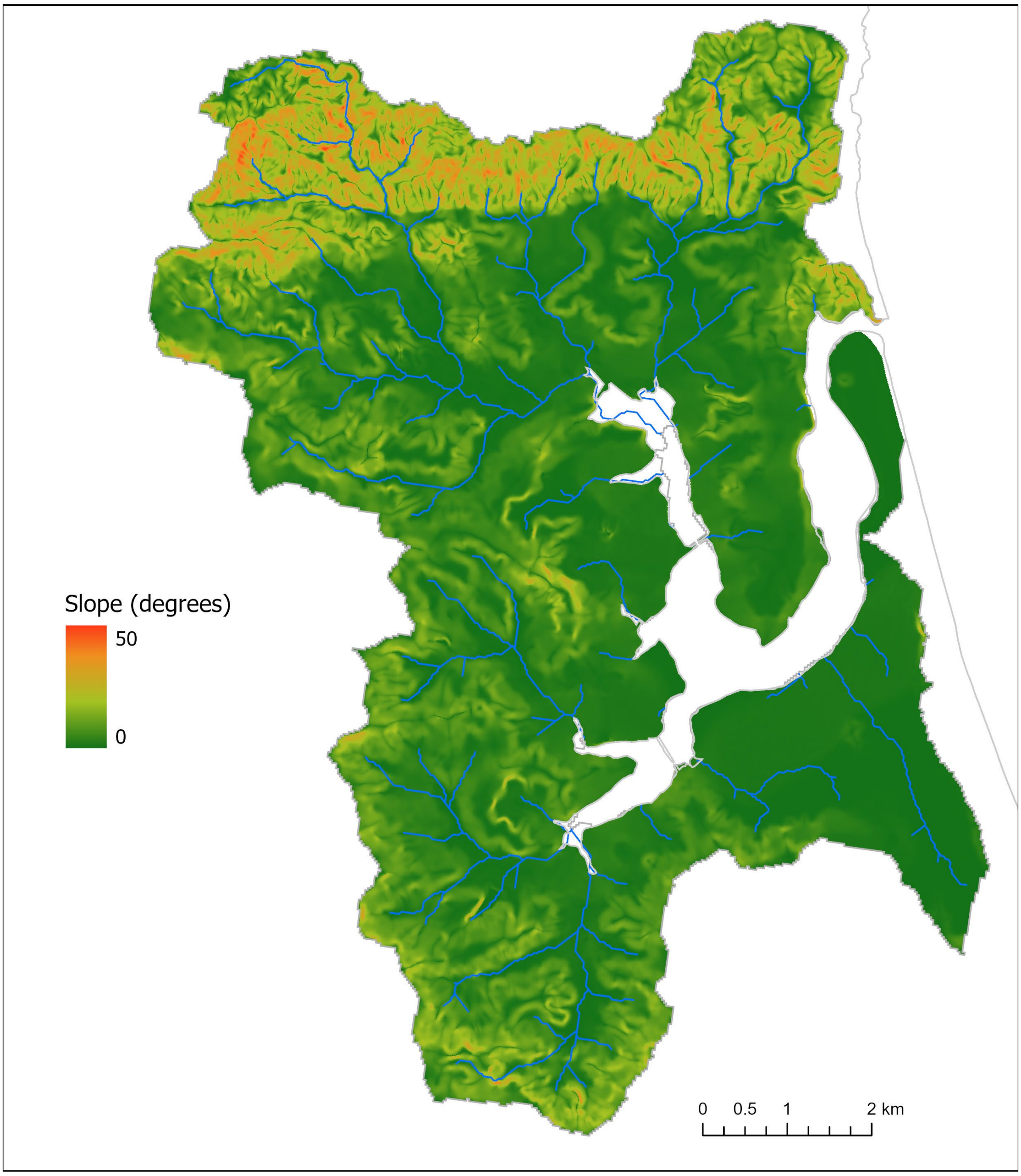

Figure 2-3: Distribution of slope in the catchment.

2.1.4 Surface geology

The surface geology was obtained from the 'toprock' attribute in Manaaki Whenua Landcare Research's (MWLR) Fundamental Soil Layer Version 1.1[4] (see Figure 2-4). The categories have been simplified for display. The surface rock type is variable. In the hills there is greywacke, sandstone/siltstone, and some argillite and welded volcanic material in the hills, while on the flats there is alluvium and peat. There are also some sandy areas. The erosion model uses erosion

[4] FSL North Island v1.1 (all attributes) | LRIS Portal (scinfo.org.nz)

terrains, as described later, which are derived from LRI (Land Resources Inventory) geology and landform information.

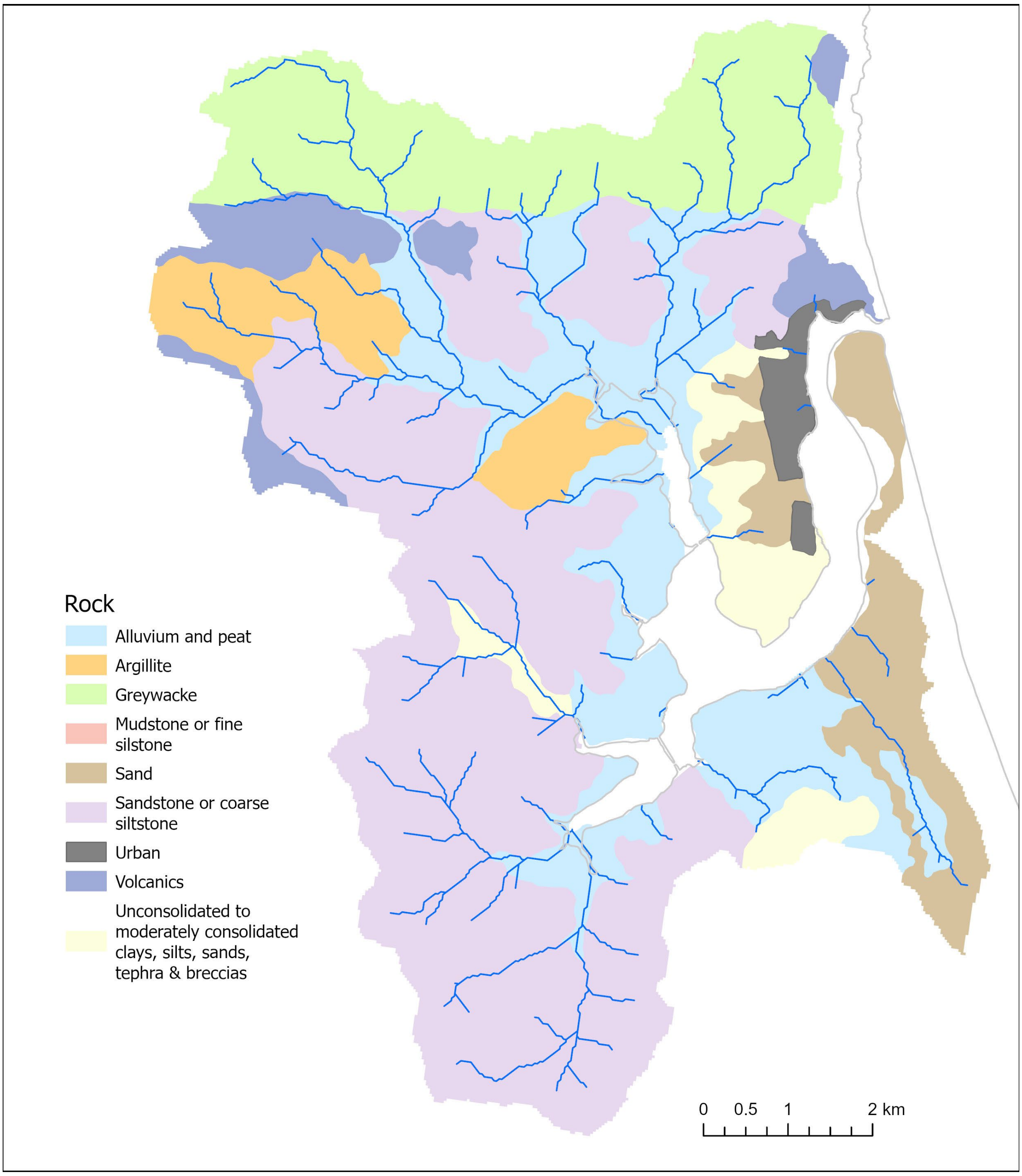

Figure 2-4: Surface rock type, derived from the Fundamental Soil Layer.

2.1.5 Climate

The NZSYE and CLUES TP and TN models use mean annual rainfall as an input. Additionally, CLUES also uses mean annual temperature as an input for the *E. coli* calculations. These climate data were taken from NIWA's 30-year climate normal grids for the period 1991-2020.

2.2 CLUES nutrient and *E. coli* modelling

2.2.1 CLUES model

CLUES (Elliott et al. 2016) is a catchment-scale, steady-state mass-budget type of model that estimates mean annual loads of TN, TP and *E. coli* for each segment in the River Environment Classification stream network (Snelder and Biggs 2002; Snelder et al. 2010). CLUES has been set-up nationally and is intended as a screening tool to support policy development and catchment planning. Contaminant loads delivered from each REC subcatchment to the stream network are estimated for each reach as a function of land use, climate and soil drainage class.

Instream loads are routed downstream taking into account stream and lake / reservoir attenuation. A full model description can be found in Elliott et al. (2016).

In this project, we used CLUES parameters that were calibrated for Northland Regional Council (Semadeni-Davies et al. 2021b). The model was calibrated against TN, TP and *E. coli* yields (mass per unit area) derived using State of the Environment (SOE) water quality data from monitoring sites in the region that have continuous flow measurement. We calibrated against yields (calculated as the mean annual contaminant load divided by upstream catchment area) to normalise the loads for upstream area, this is because large catchment areas will tend to have higher loads. The yields were log-transformed to even out the weighting of high to low flows and concentrations. The results of the calibration are given in Table 2-2.

Table 2-2: Northland CLUES calibration fit for log transformed yields.

Contaminant	Root Mean Square Error (RMSE)	Coefficient of determination (R^2)	Nash Sutcliff Efficiency (NSE)
TN	0.38	0.54	0.65
TP	0.47	0.37	0.37
E. coli	1.13	0.29	0.29

2.2.2 Wastewater treatment plant load

CLUES can add loads from point sources such as those from sewage treatment plants. For the current scenario, loads from the Mangawhai waste water treatment plant were not included in the calculations, because the plant effluent is disposed to land outside the Mangawhai Estuary catchment, into the Hakaru River catchment which leads to the Kaipara Harbour (WSP 2022).

In the future, effluent might be disposed within the Mangawhai Estuary catchment, to accommodate increased wastewater loads as the population increases, and to overcome current difficulties with land disposal outside the catchment (WSP 2022). As an option considered by Harrison Grierson (2015) treated wastewater would be partly disposed of by drip irrigation to the Mangawhai golf course, and partly to a surface wetland. Based on information in BMT WBM (2015), for wastewater loadings in 2044 there would be 78kg N/year leached from irrigation. This is unlikely to be greater than currently occurs for the golf course, because there is typically fertiliser applied to the golf course and the N application rate would be 40 kg/ha/year. BMT WBM also assessed that there would be 1200 kg N/year passed to the wetland (primarily in winter). The degree of treatment of this effluent in the wetland is uncertain, because the inflow is already well-treated. Thus the additional N loading to the estuary, probably to the Tara arm, would be about 1200 kg/year (1.2 t/year) or less, and would occur primarily in winter, which was considered in the assessment of future nutrient loading and impacts to the estuary.

2.3 Sediment load model

2.3.1 NZSYE model

Sediment loads was determined from the New Zealand Sediment Yield Estimator (NZSYE; Hicks et al. 2019). The model has previously been used for scenario modelling in Northland (Semadeni-Davies et al. 2021b). Like CLUES, NZSYE is a catchment scale annual load model that reports instream sediment loads for each REC stream segment. NZSYE uses a grid-based basis to determine sediment sources for 1 ha (100 m by 100 m) grid cells based on rainfall, terrain and lithology[5], land use and slope. The source loads are then aggregated for each REC subcatchment and are routed downstream to give estimates of instream loads. Sediment trapped in lakes and reservoirs is included in the routing. Sediment loads are adjusted to improve the match with measured sediment loads from sediment monitoring sites in the region.

2.3.2 Mature urban land use

Mature urban land use can alter sediment loads compared to pasture land-use. Sediment loads from land can be reduced due to effects such as land stabilisation and reduction in bare soil cover, while bank and channel erosion may increase due to loss of riparian vegetation and increased runoff to streams from impervious areas. The overall erosion rate depends on the degree of imperviousness, flow controls (such as infiltration devices and flow-control wetlands) and bank protection.

The national version of NZSYE does not estimate sediment loads from urban areas. Urban land use was excluded from the national NZSYE model for two key reasons: nationally it is a minor land cover and was assumed to have little impact on the sediment loads in the major river catchments that were the focus of the model's development; and, relatedly, there were too few monitoring sites with significant upstream urban areas to allow for reliable calibration. However, urban land use makes up 6 % the Mangawhai Catchment area and is a major land use in the Lower Estuary and Mouth catchments. Moreover, the future land use scenarios include further urban development.

We added urban land use as a sediment source to NZSYE using an average urban yield (22 t/km^2/year) estimated from the source yields of the Auckland Council Contaminant Loads Model (Auckland Regional Council 2010). From satellite imagery, we estimated that the urban area is predominantly medium density housing (70%) with some commercial (20%) and light industrial (10%) land uses. Measured sediment yields from Auckland (Hicks 1994) were 24 t/km^2/year for Pakuranga and 100 t/km^2/year for the moderately steep and more intensive Wairau catchment (which may also have had some recent development), so the sediment yield used in the model is reasonable. The urban sediment yield used in the model was not modified for slope, climate, soil or lithology.

As an aside, urban areas typically introduce contaminants such as zinc and copper into estuary sediment. This has not been addressed in the current assessment but may be an area to consider in the future.

[5] Derived from information provided by Manaaki Whenua / Landcare Research.

2.3.3 Additional load from the urbanisation stage

The urbanisation process, before an urban area becomes mature, can involve increases in sediment load due to a) earthworks and b) hydrological adjustment of channels (Morphum Environmental 2019).

Without controls, urban earthworks can release massive amounts of sediment (Williamson 1993; Hicks 1994), depending on factors such as slopes and area of open earthworks. Earthworks controls (such as management of timing and area of earthworks, on-site controls such as mulching, and flocculation ponds) are critical to reducing sediment loads from urban earthworks areas and are typically applied in modern developments in New Zealand (and they have been implemented around Mangawhai Central). Hicks (1994) measured a yield of 961 t/km^2/year for the urbanising Alexandra catchment (and an estimated 2370 t/km^2/year long-term annual average taking rain variation into account) which had an estimated 28% under construction. This was from an era when urban earthworks controls were more lenient than they are now. There are no good measurements in New Zealand of loads from well-controlled earthworks. Modelling studies (e.g., Beachlands South, Yalden and Semadeni-Davies 2021) suggest that an area that is developed over a season has sediment yields about 200 times that of reference pasture areas if uncontrolled, but about 10 times if controlled. Based on typical reference (no earthworks) yields of 10 t/km^2/year for flatter areas in the catchment, the erosion from controlled earthworks may be about 100 t/km^2/year. For a 100 ha (1 km^2) area developed over 5 years, the additional catchment load associated with earthworks may amount to about 20 t/year. This would increase significantly as slopes become steeper. For example, the Beachlands modelling studies (e.g., Beachlands South, Yalden and Semadeni-Davies 2021) suggest, losses from areas with slopes between 6 and 9 degrees are about 10 times that from areas with slopes between 0 and 3 degrees, and losses for slopes between 3 and 6 degrees are about 5 times that from areas between 0 and 3 degrees. This slope effect is consistent with the Universal Soil Loss Equation. There will also be a dependence on soil type. Overall, areas undergoing urban development are likely to have about 10 times the yield of equivalent pasture areas, if controlled. For typical soils where urbanisation is envisaged, indicative representative losses for controlled urban earthworks were estimated as 100 t/km^2/year for slopes of 0-3 degrees, 500 t/km^2/year for slopes between 3 and 6 degrees and 1000 t/km^2/year for slopes of 6-9 degrees.

Indicative areas and locations of future urban development over the next 30 years were derived from information provided by MMI. Assuming that the areas are developed gradually over 30 years, an annual rate of urbanisation was obtained.

Following primary earthworks, there is a period of secondary earthworks and potentially channel enlargement. If unabated, changes in flow can double channel area for 40% imperviousness (Figure 13 in Elliott et al. 2004). It is difficult to determine how this would play out in the Mangawhai urbanisation context without considering the urban drainage and channel configuration. But, for example, for a 1 km stream 1 m high and 2 m wide, bank erosion from doubling channel area would be 2000 m^3 or about 3000 t. If this occurs over 30 years, the erosion rate would be 100 t/year, if there is no mitigation. This will be considered in the context of overall catchment loading in the future scenario. While the values are uncertain, they do underscore the importance of managing runoff and channel conditions in urbanising areas.

2.4 Erosion in the future climate

The main method used to estimate sensitivity of erosion to future climate change was based on rain erosivity. Surficial erosion rates are usually related to an Erosivity value, which is in turn related to the product of storm rain energy and the and 30-minute rainfall intensity. Changes in these values were estimated from the sensitivity of rain depth and intensity to temperature. The sensitivity was the same as used by HIRDS (High Intensity Rainfall Distribution System) (Carey-Smith et al. 2018). For a 10-yar ARI event, the HIRDS 48-hour rainfall depth (which we took as an indicator of storm energy) increases by 7% for each degree increase in temperature, and the 30-minute intensity increases by 13.1%, giving a 21% increase in erosivity per degree increase in temperature, with the same proportion increase in erosion.

We used projected increases in summer temperature in conjunction with the temperature sensitivity above to estimate erosion increases. The increase in summer temperature for Mangawhai for downscaled CMIP6 (Coupled Model Intercomparison Project) climate projections[6] as determined from the average of 6 downscaled bias-corrected climate models and three emissions scenarios is shown in Table 2-3 and Figure 2-5 to Figure 2-7. The SSP1-2.6 radiative forcing scenario is considered to be low-emissions, with net zero greenhouse gas controls by mid-century, while SSP3-7.0 is considered to be a high-emissions scenario with roughly double CO_2 emissions by 2100, and SSP-4.5 is a mid-range scenario. Measured increases in summer temperature at Whangarei are about 0.25 degrees per decade since 1972[7], comparable to the projected rate of increase over the next two decades. Mean annual temperature increases were less than for summer (e.g., 2.9 degrees rather than 3.4 degrees for SSP3-7.0 in the 2080-2099 period), but summer temperature is more relevant to erosion because the largest rainfall events occur in summer at Mangawhai (based on historical data). Erosion predictions were made for 1-degree increments in summer temperature from 1 to 3 degrees.

The HIRDS temperature sensitivity is in line with sensitivity for CMIP6 climate modelling[8] for Mangawhai. The climate models predicts an increase in 99th percentile summer daily rain[9] of 29.4% for SSP3-7.0 for 2080-2099, which is associated with a 3.4 °C temperature increase. The HIRDS approach would predict an increase of 8.1% per degree change in temperature for a 24-hour period and 10-year return interval, or 27.5% rainfall increase for 3.4 °C temperature increase, which is in line with the CMIP6 99th percentile. It is also noted that projected percent increases in less frequent rainfall from CMIP6 climate models are greater than for the 99th percentile (unpublished NIWA data).

A second method for estimating erosion under climate change was explored. It is based on changes in mean annual flood and the relationship between storm flow and sediment. Typically, storm event sediment load increases with flow rate with peak flow raised to a power, where the exponent has been observed from several studies to be in the range from 1.2 of 2.9 (Basher et al. 2011). Values from Auckland (Hicks 1994) were in the range of 1.2 to 2.2. A value of 1.5 has been adopted for our analysis as a representative mid-range value. Changes in mean annual flood were determined from previous modelling by NIWA, based on the TopNet hydrological model and CMIP5 climate projections. Corresponding flood values for CMIP6 have not been determined. Nevertheless, we conducted some analysis with CMIP5, using CMIP5 temperature increases in Appendix A to relate the scenarios to temperature increases.

Climate change impacts in the other components of the broader Sustainable Mangawhai Project outside this project (such as inundation assessment) will be likely made based on sea level rise projections. Sea level rise can be related to temperature increases in the following way. Sea level rise

[6] Aotearoa New Zealand climate projections | Ministry for the Environment; Climate Projections Map (environment.govt.nz)
[7] Temperature | Stats NZ
[8] Climate Projections Map (environment.govt.nz)
[9] 99th percentile includes days with no rain, although that could be updated in future model outputs.

predictions over time are available for various climate scenarios corresponding to CMIP6 scenarios[10]. Typically, for coastal impact work, a specified sea level rise increment is specified. This increment can be related to a particular time period for a particular emissions scenario. For example, for Site 893 at Mangawhai, a 0.6 m relative sea level rise (including effects of vertical land movement, VLM), will be reached in 2080 for the SSP2-4.5 scenario. The corresponding temperature increase from Figure 2-7 is 1.6 °C (compared with an average based around 2024). The associated increase in erosion can be determined from this increase in temperature. The results could differ depending on the emissions scenario, and whether VLM is incorporated. For example, for the SSP3-7.0 scenario, the year corresponding to a 0.6 m rise is 2070, and the temperature increase is 1.8 degrees. For the SSP1-2.6 scenario the year is 2090, and the temperature increase is 0.4 degrees. This example suggests that for a fixed sea level rise, there can be different associated temperature increases, depending on the scenario. While SSP1-2.6 starts to reverse temperatures towards 2100, relative sea level still increases due to a) vertical land movement and b) long timeframes associated with sea level rise.

Neverman et al. (2023) assessed increases in erosion under climate change. We did not adopt that approach or their results for the following reasons. Their change in surficial erosion was based on mean annual rainfall, whereas we have incorporated aspects of rainfall intensity that are more relevant than mean annual rainfall. They applied a method for increases in landslide sources, but that is not relevant for the Mangawhai catchment where there is not high landslide susceptibility, due to the lithology and slope. They applied an adjustment to 'bank erosion' based on mean annual flood flow, similar to our flow-based approach, although they used an exponent of 1 rather than our representative value of 1.5.

Table 2-3: Increase in mean summer temperature (°C) for Mangawhai relative to 1995-2014, for various future periods and pathway-emission scenarios, averaged over six climate models.

	2021-2040	2041-2060	2080-2099
SSP1-2.6	0.6	0.6	0.8
SSP2-4.5	0.6	1.2	1.5
SSP3-7.0	0.8	2.1	3.4

[10] https://searise.takiwa.co/map

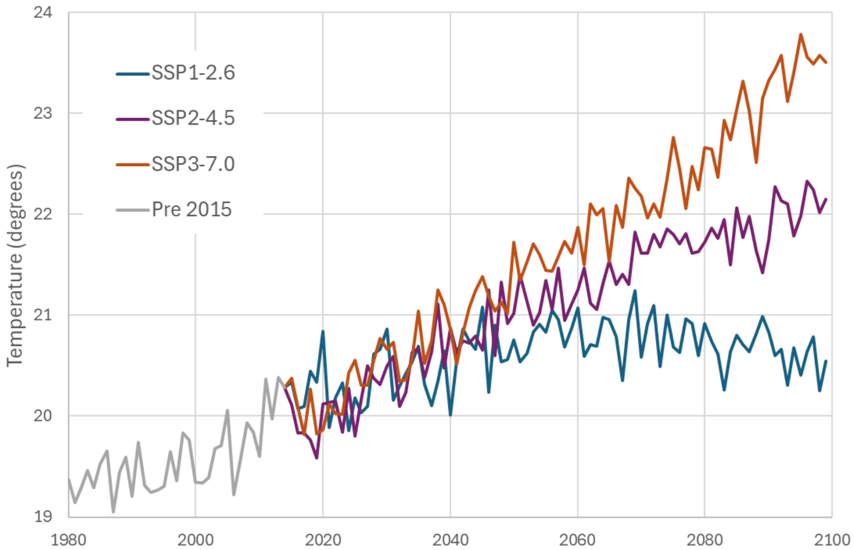

Figure 2-5: Summer mean temperature over time for CMIP6 for three climate scenarios, averaged over 6 models.

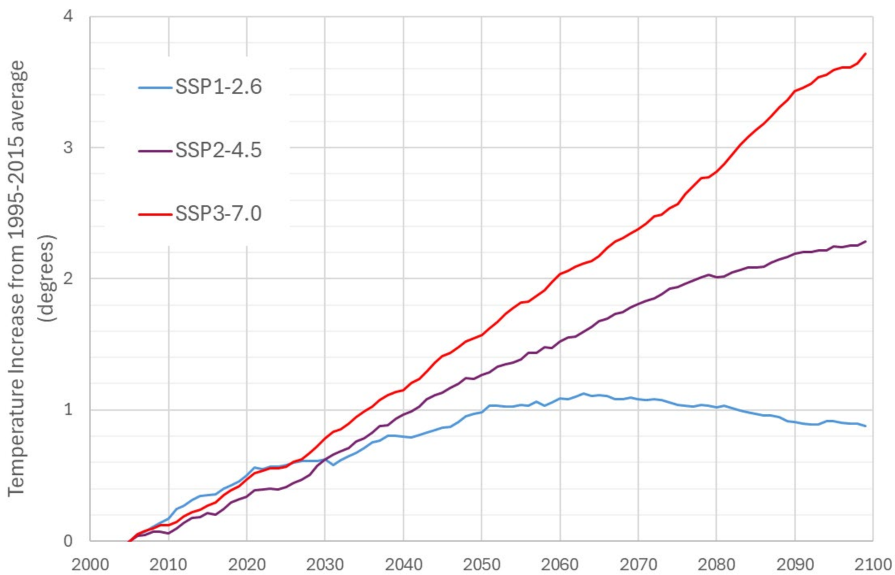

Figure 2-6: Increase in summer mean temperature compared with 1995-2014 average for CMIP6 for three emissions scenarios, averaged over 6 models. Values are based on a 20-year mean centred around the value on the horizontal axis.

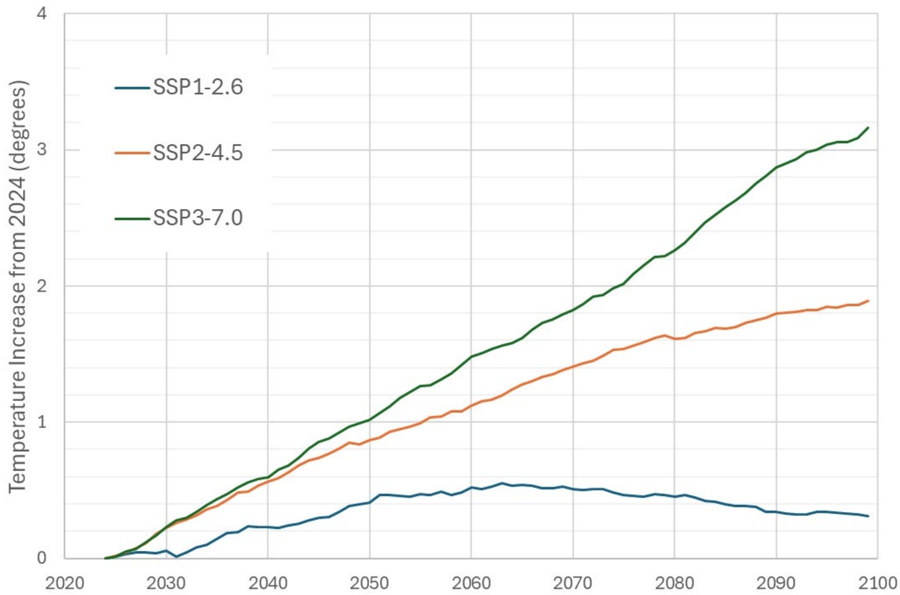

Figure 2-7: Increase in summer mean temperature compared with 2024 for CMIP6 for three emissions scenarios, averaged over 6 models. Values are based on a 20-year mean centred around the value on the horizontal axis.

2.5 Estuary sedimentation

Sedimentation processes in estuaries are complex, involving many processes including: episodic inputs from the catchment; dispersal by currents; flocculation; settling; flushing to the ocean; resuspension due to currents, waves and biota; and subsequent redistribution and settling.

In the short term during and shortly after events, sediment can deposit on the bed and result in impacts on biota. Sediment can accumulate over time due to the net long-term excess of sedimentation over resuspension, which can affect estuary depths and habitat suitability. A further risk which was not addressed in this study, is accumulation of fine sediment where there was previously coarser sediment, resulting in increased muddiness, which has significant ecological implications.

In this study, a highly simplified approach was used to obtain a gauge of sedimentation risks. This involved distributing the mean annual load of sediment from a source area (the catchment associated with an estuary compartment) into various deposition compartments of the estuary, according to pre-defined distribution proportions. This is repeated across the different source areas, to arrive at the total mass of sediment deposited in the deposition compartment. The total sediment deposition mass to an estuary compartment was then converted into a depth of deposition by spreading the mass over the area of the compartment excluding the low tide channel and converting from a mass to a volume using bulk density of 1.25 t/m^3. There is considerable uncertainty about the distribution proportions, so two sets of assumptions (associated with lower and higher deposition fractions) were explored.

In previous compartment-based modelling studies (in other estuaries), the distribution proportions were determined from a combination of observed deposition rates, detailed estuary deposition modelling, and sediment source tracing studies. Such data or models are not available for

Mangawhai Harbour, although they could be generated in the future. The proportions were assessed on knowledge of estuarine dynamics in the Mangawhai Harbour context and results of other estuary deposition studies (Green 2013; Green 2015):

- The Southern Arm and Tara Arms have low accommodation volume for sediment. They have a main channel with elevated areas to the side which would have a low inundation period. These areas are likely to be ebb-tide dominated (stronger ebb currents than flood currents), and to flush fairly well. Accordingly, low deposition fractions were assigned for source areas associated with these estuary compartments, and zero deposition fractions for sources associated with other estuary compartments.
- Back Bay could serve to capture a significant proportion of the sediment derived from the Southern Arm, Tara Arm, and Back Bay. Flows from the arms will decelerate, potentially flocculate and settle in this area. While sediment inflow derived from lower in the estuary may make its way up into this part of the estuary, the proportion will be small, and the sources from those down-estuary areas are relatively small, so they were assigned a zero deposition fraction in Back Bay.
- The mid and lower estuary may receive some deposits derived from sources further up the estuary. A low proportion was assigned, however, as those areas can have moderate currents over the flats, and hallow wind waves due to the exposure and fetch, both of which make deposition less likely and can lead to resuspension.
- The mouth was assigned zero deposition as it has high currents and sandy sediment.

The resulting distribution proportions are shows in Table 2-4 and Table 2-5. Note that in the high deposition scenario, the sum of destination proportions from a source catchment (sum down a column, apart from the final row) is sometimes greater than one, but that is acceptable as the intention is to represent a high scenario for each compartment, rather than a complete budget for the fate of a source. For both tables, the sum of destination proportions from a source catchment (sum down a column, apart from the final row) can sum to less than one because some sediment can be lost outside the estuary mouth. The final row of the tables represents spreading a proportion of the total load to the estuary evenly over the non-channel part of the estuary (25% of the catchment sediment spread evenly over the estuary in the low deposition scenario, and all the catchment sediment spread evenly over the estuary for the high-deposition scenario. Hence the values in the last rows are not directly related to the values in other columns.

Table 2-4: Distribution proportions (proportion of sediment load from a source area that is deposited in the deposition area), for the low deposition scenario.

Deposition compartment	Source area					
	Southern Arm	Tara Arm	Back Bay	Mid Estuary	Lower Estuary	Mouth
Southern Arm	0.1	0	0	0	0	0
Tara Arm	0	0.1	0	0	0	0
Back Bay	0.25	0.25	0.25	0	0	0
Mid Estuary	0.05	0.05	0.05	0.05	0	0
Lower Estuary	0.05	0.05	0.05	0.05	0.05	0
Mouth	0	0	0	0	0	0

Deposition compartment	Source area					
	Southern Arm	Tara Arm	Back Bay	Mid Estuary	Lower Estuary	Mouth
Overall estuary	0.25	0.25	0.25	0.25	0.25	0.25

Table 2-5: Distribution proportions (proportion of sediment load from a source area that is deposited in the deposition area), for the high deposition scenario.

Deposition compartment	Source area					
	Southern Arm	Tara Arm	Back Bay	Mid Estuary	Lower Estuary	Mouth
Southern Arm	0.25	0	0	0	0	0
Tara Arm	0	0.25	0	0	0	0
Back Bay	0.5	0.75	0.5	0	0	0
Mid Estuary	0.2	0.2	0.2	0.2	0	0
Lower Estuary	0.2	0.2	0.2	0.2	0.2	0
Mouth	0	0	0	0	0	0
Overall estuary	1	1	1	1	1	1

2.6 Estuary eutrophication

Estuary eutrophication was estimated using components of the Estuarine Tropic Indicator (ETI) tool (Plew et al. 2020), which is tailored to New Zealand conditions, and has been applied widely in New Zealand. The tool mixes catchment nutrient loads into the estuary to determine a potential nutrient concentration (where the 'potential' indicates that the estimate is made without considering nutrient uptake). This calculation takes account of flushing of the estuary and incoming nutrients from coastal water.

The potential nutrient concentration is then graded in relation to the potential to cause macroalgal growth, based on empirical relationships between potential nutrients and an index of macroalgal abundance. A phytoplankton (small suspended algae) concentration in summer is determined using a simple phytoplankton growth model.

The analysis was only conducted for nitrogen loading, as the estuary is not likely to be responsive to phosphorus inputs, given the moderate amount of flushing and the amount of phosphorus in oceanic water.

The band thresholds for TN in relation to macroalgal abundance are (Plew 2024):

A: TN < 175 mg m^{-3}

B: 175 < TN < 335 mg m^{-3}

C: 335 < TN < 495 mg m^{-3}

D: TN > 495 mg m^{-3}

These calculations give an indication of estuary-wide eutrophication, and do not take account of sub-estuary-scale variations.

The following estuary parameters were used:

- Volume 9,718,917 m^3 (from Hydrosystems of New Zealand)[11].
- Tidal prism 6,562,592 m^3 (from Hydrosystems of New Zealand)
- Freshwater inflow (mean) 1.278 $m^3\ s^{-1}$ (from flows in NZ River Maps)[12]
- Summer mean inflow 0.47 $m^3\ s^{-1}$ (from February flows in NZ River Maps)

2.7 Web mapping

Key input and output layers for the model were incorporated into an ArcGIS Online web map, which is available publicly from the link Mangawhai Contaminant Loading web map[13].

[11] NZ Coastal Hydrosystems | MfE Data Service)
[12] NZ River Maps (niwa.co.nz)
[13] https://niwa.maps.arcgis.com/apps/dashboards/64d31875b6ec48fc90a8d9ac75ec3417

3 Results

3.1 Current catchment loads to the estuary

3.1.1 Nutrients

The estimated mean annual loads for TN and TP to the estuary are 55.4 t/y and 5.8 t/y respectively. The loads are broken down by land use and estuary compartment in Table 3-1 and Table 3-2, and Table 3-6. Sediment load to each estuary compartment, the breakdown by land use, and load per catchment area (sediment yield) are shown in Table 3-6.

The estimated generated loads for TN and sediment are mapped in Figure 3-1 as examples of model outputs – these and other outputs are available for display in the web mapping tool.

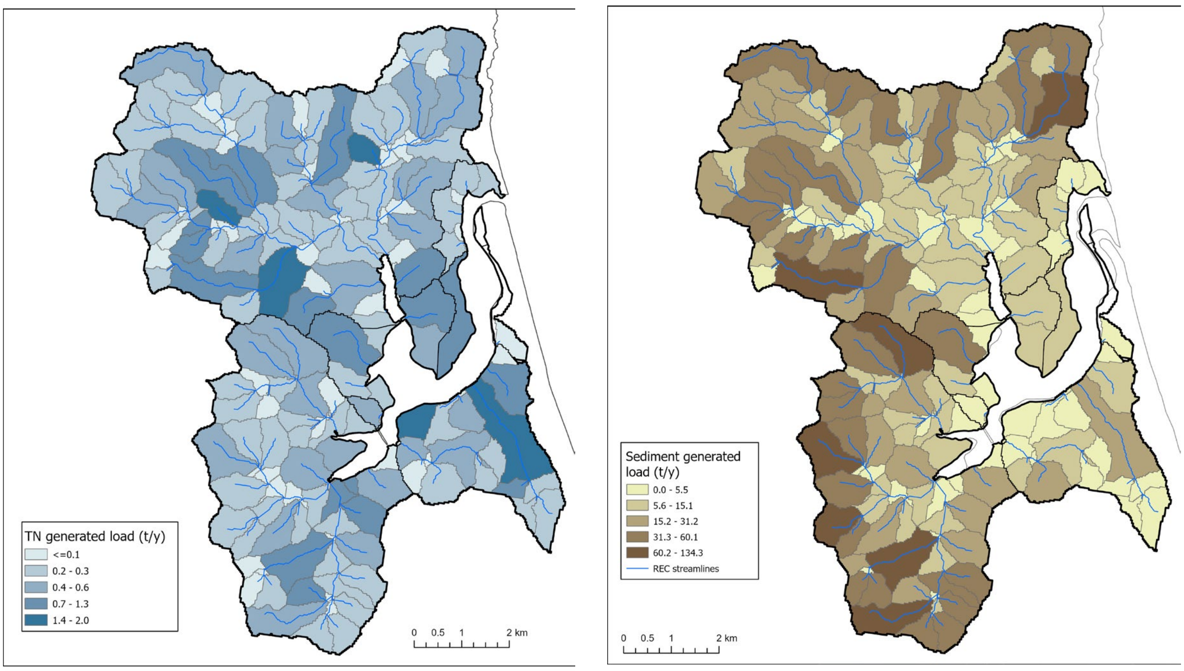

Figure 3-1: Example modelled outputs; subcatchment generated loads for TN and sediment. Mapped using Jenks distribution.

Crops and horticulture provide a surprisingly large proportion (31%) of the nitrogen load, considering the relatively small proportion (2%) of the catchment occupied this class of land use. This result derives from the large nutrient yield from the Northland nutrient model (12 t/km^2/y, or 120 kg/ha/y), which was in turn influenced by high measured loads from some catchments with avocados in the Northland CLUES model calibration dataset. In reality, horticulture land uses in the Mangawhai catchment are viticulture and olives that are likely to have relatively low yields. Avocados can yield high N losses, depending on how they are managed, but avocado growing on Tara hill would drain to the Hakaru catchment outside the Mangawhai catchment. Market gardens can also have high losses, but there is minimal market gardening in the catchment. This sensitivity to land use type points to the desirability of paying attention to the particular type of crop or horticultural land use if nitrogen proves to be a concern. This situation could be rectified by adjusting model parameters, but model recalibration is beyond the scope of this project.

Table 3-1: CLUES estimated mean annual TN loads (t/y) delivered to each estuary compartment by land use type. The percentages not in italics refer to the breakdown of load by land use, while the percentages in italics (last column) are the refer to the breakdown of load by compartment. Land uses that are not present in a compartment catchment are indicated with a dash.

Estuary compartment	Dairy	Sheep and Beef	Deer and other stock	Forest and scrub	Crops and horticulture	Urban	Other land uses	Compartment total
Southern Arm	6.33 (40%)	3.12 (20%)	1.24 (8%)	1.19 (8%)	3.4 (22%)	0.26 (2%)	0.11 (1%)	15.66 *(28.3%)*
Tara Arm	5.12 (19%)	4.5 (17%)	2.06 (8%)	4.73 (17%)	9.83 (36%)	0.74 (3%)	0.25 (1%)	27.23 *(49.1%)*
Back Bay	<0.01 (<1%)	0.4 (16%)	0.32 (13%)	0.24 (10%)	0.55 (22%)	0.9 (37%)	0.04 (2%)	2.45 *(4.4%)*
Mid Estuary	2.28 (28%)	1.61 (20%)	0.25 (3%)	0.46 (6%)	3.23 (40%)	0.15 (2%)	0.16 (2%)	8.14 *(14.7%)*
Lower Estuary	-	0.09 (9%)	-	0.06 (6%)	-	0.6 (58%)	0.29 (27%)	1.04 *(1.9%)*
Mouth	-	0.04 (4%)	-	0.16 (18%)	-	0.67 (72%)	0.06 (6%)	0.92 *(1.7%)*
Total catchment	**13.74 (25%)**	**9.76 (18%)**	**3.88 (7%)**	**6.84 (12%)**	**17 (31%)**	**3.32 (6%)**	**0.91 (2%)**	**55.43 (100%)**

Table 3-2: CLUES estimated mean annual TP loads (t/y) delivered to each estuary compartment by land use type. The percentages not in italics refer to the breakdown of load by land use, while the percentages in italics (last column) are the refer to the breakdown of load by compartment. Note a further 0.2 t/y of phosphorus is associated with soil loss. Land uses that are not present in a compartment catchment are indicated with a dash.

Estuary compartment	Dairy	Sheep and Beef	Deer and other stock	Forest and scrub	Crops and horticulture	Urban	Other land uses	Compartment total
Southern Arm	1.38 (61%)	0.74 (32.8%)	0.06 (2.7%)	0.04 (1.9%)	<0.01 (0.2%)	0.03 (1.1%)	0.01 (0.2%)	2.27 *(41.2%)*
Tara Arm	0.92 (40.9%)	1.05 (46.4%)	0.04 (2%)	0.14 (6.1%)	0.01 (0.5%)	0.08 (3.7%)	0.01 (0.5%)	2.26 *(41.0%)*
Back Bay	<0.01 (0.4%)	0.06 (35.6%)	0.01 (4.1%)	0.01 (4.5%)	<0.01 (0.4%)	0.09 (54.2%)	<0.01 (0.9%)	0.17 *(3.1%)*
Mid Estuary	0.34 (51.5%)	0.24 (36.5%)	0.01 (1.5%)	0.04 (5.6%)	0.01 (0.9%)	0.02 (2.6%)	0.01 (1.4%)	0.66 *(12.0%)*
Lower Estuary	-	<0.01 (3%)	-	<0.01 (2.4%)	-	0.05 (78%)	0.01 (16.6%)	0.06 *(1.1%)*
Mouth	-	0.01 (7.2%)	-	0.01 (5.9%)	-	0.07 (84.7%)	<0.01 (2.2%)	0.09 *(1.6%)*
Total catchment	**2.65 (48%)**	**2.1 (38.2%)**	**0.12 (2.2%)**	**0.23 (4.2%)**	**0.02 (0.4%)**	**0.35 (6.3%)**	**0.04 (0.7%)**	**5.51 (100%)**

CLUES has an approximate method for estimating concentrations from loads (Oehler and Elliott 2011). These concentrations were compared with measured concentrations to give an idea of model performance. Concentrations have been measured previously by Valois (2017) over approximately a year from 2016 to 2017 at six sites, three of which were non-saline (Table 3-3). Comparison of concentrations estimated from CLUES with measured concentrations for the three non-saline sites (Table 3-4) provides some reassurance that the model is providing reasonable predictions, given the uncertainties in the measurements and method to calculate concentrations from loads. Possibly the loads for TN are a bit high, which should be borne in mind when assessing eutrophication risks. This may be in part due to the potential over-prediction of losses from the crop and horticulture land use, as discussed above. Note that typically with CLUES models, we estimate baseline concentrations from a separate statistical model, rather than using the approximate method above. Those results are also shown in Table 3-4.

Table 3-3: Measured concentrations from freshwater sites, from Valois (2017). The number before parentheses is the median concentration, while the numbers in parentheses are the range.

Metric	Forest Stream	Tara Creek	Devich Road bridge
Predominant land use	Native	Mixed native and pasture	Pasture
Number of samples	26-28	26-28	26-28
TP (mg/L)	0.04 (0.02-0.08)	0.08 (0.04-0.36)	0.07 (0.03-1)
TN (mg/L)	0.24 (0.08-0.49)	0.49 (0.07-1.5)	0.46 (0.24-3.3)
NH4-N (mg/L)	0.008 (0.005-0.01)	0.06 (0.01-0.44)	0.03 (0.01-0.48)
E. coli (MPN/100 mL)	115 (10-6500)	590 (100-21,000)	215 (68-20,000)

Table 3-4: Comparison between CLUES concentrations and measured concentrations.

	TN (g m^{-3})		TP (g m^{-3})	
Location	**CLUES**	**Measured**	**CLUES**	**Measured**
Forest Stream	0.36	0.24	0.019	0.04
Tara Creek	0.75	0.49	0.08	0.08
Devich Road Bridge	0.51	0.46	0.17	0.07

3.1.2 *E. coli*

The *E. coli* load delivered to the estuary is 2.5×10^{15} organisms/year, and the breakdown by land use and estuary compartment is shown in Table 3-5. In terms of land use, most (87%) of the load comes from pastoral land uses. Most of the load comes from the Southern and Tara arms.

Table 3-5: CLUES estimated mean annual E. coli loads (10^{15} organisms/y) delivered to each estuary compartment by land use type. The percentage of the total load for each section is given in parentheses. Land uses that are not present in a compartment catchment are indicated with a dash.

Estuary compartment	Dairy	Sheep and Beef	Deer and other stock	Forest and scrub	Crops and horticulture	Urban	Other land uses	Compartment total
Southern Arm	0.38 (41%)	0.35 (38%)	0.14 (16%)	0.02 (2%)	<0.01 (<1%)	0.01 (2%)	<0.01 (<1%)	0.92
Tara Arm	0.28 (25%)	0.48 (43%)	0.21 (18%)	0.12 (10%)	0.01 (1%)	0.04 (3%)	0.01 (<1%)	1.14
Back Bay	<0.01 (<1%)	0.04 (32%)	0.03 (26%)	<0.01 (3%)	<0.01 (<1%)	0.05 (38%)	<0.01 (1%)	0.12
Mid Estuary	0.09 (34%)	0.15 (54%)	0.02 (7%)	<0.01 (1%)	<0.01 (1%)	0.01 (3%)	<0.01 (1%)	0.27
Lower Estuary	-	0.01 (18%)	-	<0.01 (2%)	-	0.04 (67%)	0.01 (12%)	0.05
Mouth	-	<0.01 (10%)	-	<0.01 (6%)	-	0.03 (80%)	<0.01 (3%)	0.04
Total catchment	**0.76 (30%)**	**1.04 (41%)**	**0.4 (16%)**	**0.15 (6%)**	**0.01 (<1%)**	**0.17 (7%)**	**0.02 (1%)**	**2.55**

3.1.3 Sediment

Sediment load to each estuary compartment, the breakdown by land use, and load per catchment area (sediment yield) are shown in Table 3-6. Sediment yields are mapped in Figure 3-2.

Table 3-6: Estimated mean annual sediment loads (t/y) delivered to each estuary compartment by land use type. The percentage of the total load for each section is given in parentheses. The sediment yield is based on the catchment area associated with the arm.

Estuary compartment	Herbaceous	Other	Trees	Urban	Compartment total	Sediment yield (t/km²/year)
Southern Arm	1105.6 (80%)	0 (0%)	263.8 (19%)	4.3 (0%)	1373.7	69.1
Tara Arm	864.1 (60%)	2.3 (0%)	554.5 (39%)	14.8 (1%)	1435.7	40.1
Back Bay	35.4 (50%)	0 (0%)	18 (25%)	17 (24%)	70.4	20.8
Mid Estuary	75.2 (81%)	6.6 (7%)	8 (9%)	2.7 (3%)	92.5	11.5
Lower Estuary	2.8 (19%)	2.8 (20%)	0.9 (6%)	7.9 (55%)	14.4	8.2
Mouth	1.8 (9%)	0 (0%)	6.2 (30%)	12.7 (61%)	20.7	13.2
Total catchment	2085 (69%)	11.7 (0%)	851.4 (28%)	59.5 (2%)	3007.5	42.7

The low to moderate average sediment yield reflects the geology and slopes. The generally low erosion rate is consistent with geologies of sandstone/siltstone and occasionally welded volcanic material in the hilly pasture areas (Figure 2-4), all of which are moderately strong, and alluvium or peat in flatter areas. The rock types in the hilly areas typically need slopes of greater than 24 degrees to pose a landslide risk (Dymond and Shepherd 2023), but slopes in the hilly pasture areas are less than 24 degrees (Figure 2-3). In the Brynderwyn hills (the hilly areas in the north of the catchment), slopes greater than 24 degrees are common and there is greywacke surface rock type. However, there is low erosion risk from the Brynderwyn area as the area is mostly vegetated with native vegetation (plus a small area of forestry).

There are no areas of Highly Erodible Land (HEL) in the catchment, according to assessments by MWLR for the Ministry for the Environment of areas subject to landslides gully erosion and earthflow. This is consistent with observations in the catchment. Aerial imagery in Google Earth post Cyclone Gabriele does not show evidence of landslides in the catchment from that storm (but there were landslides in the Kaipara catchment, near Hoteo).

There is a considerable variation of estimated erosion across the catchment, ranging from around 10 t/km^2/year in the lower and flatter parts of the catchment with alluvium, to hot-spots of about 250 t/km^2/year (and up to 420 t/km^2/year) in the steeper hilly areas around the southern and western ridgelines and southwest of the Tara Creek catchment with sandstone/siltstone geology (Figure 2-3 and Figure 2-4). This variation in sediment yield reflects variation in slope, land cover, and geology. The hot-spot areas are fairly small, so that catchment-average erosion is much less than the hot-spot values. Such hot-spots offer opportunities for reducing erosion, although their area and associated influence on sediment loads is limited, and some erosion controls such as riparian and valley vegetation are already in place.

The predicted yields are broadly consistent with those from the empirical model NZEEM (New Zealand Empirical Erosion Model) (2016 version, downloaded from the Manaaki Whenua Landcare Research LRIS portal, result not presented here)[14]. A difference is that NZEEM predicts annual erosion of around 500 t/km^2/year in steeper pasture areas in the northeast of the catchment (Mangawhai Estates).

The predicted sediment yields are line with what would be expected based on measurements in similar catchments. For example, Hicks (1994) observed 46 t/km^2/year in the Manukau at Somerville catchment, which at the time was in pasture, and Mahurangi Stream the yield was 49.1 t/km^2/year (Hicks et al. 2019)

Most of the sediment load (93.6%) from the catchment enters in the Tara Arm and the Southern Arm, each contributing roughly the same amount. The load from the Back Bay and mid-lower estuary subcatchments is relatively small, reflecting the relatively small area and the relatively small yields (see Table 3-6).

[14] NZEEM (Erosion Rates) North Island | LRIS Portal (scinfo.org.nz)

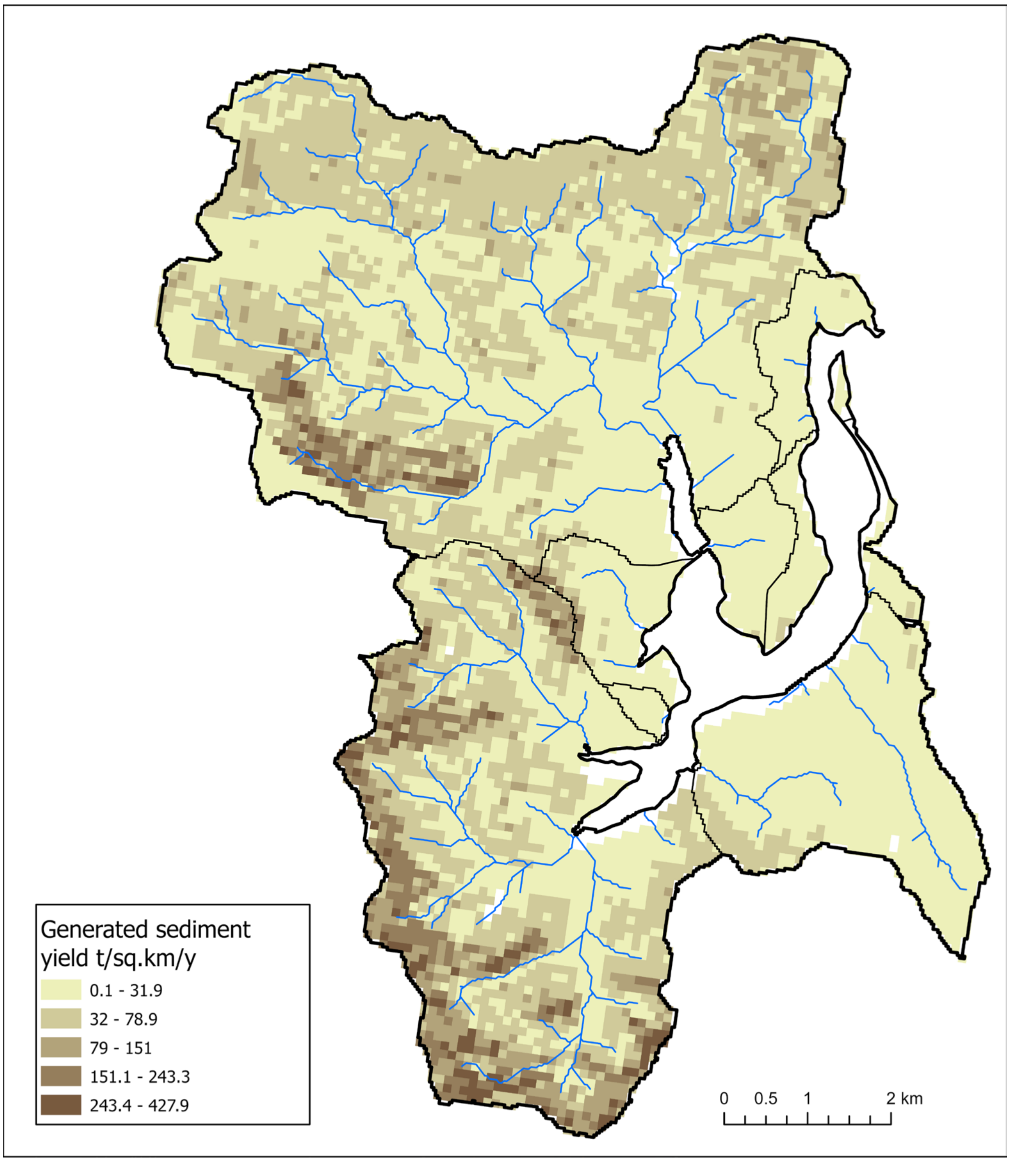

Figure 3-2: Predicted erosion rates (t/km^2/year) across the catchment for the current scenario Catchment boundaries and river-lines are included for reference.

3.2 Sediment loads for the climate change scenario

Changes in sediment loading for the future climate scenario are shown in Table 3-7 for the rainfall erosivity method for different temperature increases and subcatchments. This shows the potential for considerable increases (a factor of 1.63, or 63% increase) for a 3 °C temperature increase. This ratio applies for all the subcatchments, because the factor increase in erosion is based on temperature increases that are uniform across the catchment. These temperature increases can be related to climate change scenarios and time periods using Figure 2-7.

Table 3-7: Sediment loading (kt/year) under for various temperature increases using the rainfall erosivity method.

Compartment	Increase in summer temperature (°C)			
	0	1	2	3
Southern Arm	1373.7	1662.2	1950.7	2239.1
Tara Arm	1435.7	1737.2	2038.7	2340.2
Back Bay	70.4	85.2	100.0	114.8
Mid Estuary	92.5	111.9	131.4	150.8
Lower Estuary	14.4	17.4	20.4	23.5
Mouth	20.7	25.0	29.4	33.7
Total catchment	3007.5	3639.1	4270.7	4902.2
Ratio compared with 0ºC	1	1.21	1.42	1.63

The second approach to estimate increases in sediment load was the flood-based method. Increases in mean annual flood for CMIP5, as determined by climate projections and flood modelling (Collins 2020) (data provided by Christian Zammit, NIWA) are shown for selected reaches for the RCP8.5 emissions scenario in Table 3-8. The predicted erosion increase is a factor of about 1.58 for 2080-2089. This can be compared with the increase from the erosivity method as follows. The CMIP5 increase in temperature for RCP8.5 for Whangarei is 2.6 °C degrees (see Appendix A). The erosion factor increase of about 1.58 for the flood-based method aligns with the increase associated with 2 degrees temperature increase from the erodibility method, so the two methods give roughly comparable results.

We decided not to use the flood method (the second approach) in later sections of the report. Flows determined from downscaled climate models and a hydrology model involve considerable uncertainty, because the climate downscaling is not tuned to extreme events for CMIP5, and the hydrology models entail considerable uncertainty. The flood predictions in Collins (2020, their Figure 5) predict statistically insignificant increases in the mean annual flood event for the high emissions scenario in 2080-2090 for most locations in the North Island, contrasting with CMIP6 predictions of increases in summer 99th percentile rainfall. CMIP6 has paid more attention to extreme rainfall, and new hydrological simulations based on CMIP6 may prove to be more useful. Considering this uncertainty, in later sections of this report, we focus on the erosivity method, which is based on HIRDS predictions.

Table 3-8: Mean annual flood changes and estimated associated erosion change. Flows are from CMIP5 hindcast period, from the TopNet hydrology model averaged across six downscaled climate models, for the RCP8.5 emissions scenario.

Stream	NZSegment ID	Hindcast mean annual flood (1995-2014)	Flow Ratio 2080-2099	Erosion ratio, from hindcast to 2080-2099
Tara	1027542 and 1027432	15.0	1.35	1.57
South arm	1028251	4.9	1.37	1.60

3.3 Load for the future land use scenario

3.3.1 Nutrients

Mangawhai is undergoing extensive and rapid land use change. There has been considerable urbanisation, and this is planned to accelerate. Areas of grazing farms have been converted to low-density rural developments in the hinterland. It is understood that while there used to be some 14 dairy farms in the catchment, there is now just one (pers. comm., Phil McDermott).

Future increases in TN loads are likely to be insignificant. Urban land use has TN yields (8 kg/ha/year) comparable to pasture areas, according to the Northland CLUES model, so future urbanisation is unlikely to increase TN loads to the estuary significantly.

The increase in load due to potential future sewage disposal into the catchment is estimated to be 1.2 t/year or less (see Section 2.2.2), which is small in relation to the current load to the Tara arm (27.2 t/year) and only about 2.7 % of the total estuary catchment inputs of 55.4 t/year.

A proviso is that if that widespread nutrient-intensive horticulture were introduced (e.g., market gardens or intensive avocadoes) there could be risks from eutrophication via increased nutrient loads to the estuary. For example, if 500 ha of intensive horticulture with losses of 120 kg/ha were introduced, the associated load would be about 60 t/year, or approximately a doubling of TN load to the estuary. This is unlikely, because there are limited suitable areas for such enterprises in the catchment, and there is pressure for urbanisation or large lot development in the catchment.

3.3.2 Sediment

In terms of sediment, a land-use related risk is increased erosion due to urban earthworks and channel erosion associated with hydrological adjustment, as discussed in Section 2.3.3. For controlled urban earthworks, estimated sediment loads are 100 t/km^2/year for slopes of 0-3 degrees, 500 t/km^2/year for slopes between 3 and 6 degrees and 1000 t/km^2/year for slopes of 6-9 degrees (as discussed in Section 2.3.3).

Representatives of MMI (Phil McDermott) have used knowledge of the District Plan and other proposed developments to prepare an indicative map of anticipated urbanisation. The general locations of anticipated development are shown in Figure 3-3. We have ignored large lot residential development and rural lifestyle areas, which are likely to become widespread through the catchment, because the development of such areas does not generally involve large-scale earthworks. The approximate total area of urbanisation, distribution of slopes, receiving arm, and sediment load is show in Table 3-9. Note that the slope proportions are only approximate as the precise location of development is unknown. In the model, this load is spread over the duration of the development.

Figure 3-3: Map depicting general locations of anticipated urbanisation (orange dots). The base map is from Open Street Maps.

Table 3-9: Anticipated development areas.

Development name	Estuary compartment	Residential earthworks area (ha)	Slope			Additional sediment load (t)
			0-3 degrees	3-6 degrees	6-9 degrees	
Mangawhai Central	Tara (75%) Back Bay (25%)	218	100%	-	-	218
The Rise	Tara	57	50%	25%	25%	242
The Hills	Southern	57	60%	20%	20%	205
Mangawhai East	Back Bay	93	100%	-	-	93

The annual load smoothed over a 10-year earthworks period is compared with the load from the current land use in Table 3-10. For estuary segments, load proportions relate only to the load from the catchment associated directly with catchment arm (rather than loads that may be transported from other parts of the estuary). For the final row, the load proportion relates to the load to the estuary overall.

Table 3-10: Sediment load from urbanisation compared to the current load.

Estuary Segment	Current load (t/year)	Earthworks sediment load (t/year)	Earthworks sediment as a proportion of current sediment
Tara	1373.7	20.5	1.5%
Southern	1435.7	40.6	2.8%
Back Bay	70.4	14.8	21.0%
Total leading to Back Bay	2879.8	75.8	2.6%
Total estuary	3007.5	75.8	2.5%

These proportions are fairly low despite areas of earthworks having a high yield (load per area) relative to existing land use because:

A. The area of earthworks per year is small in relation to the overall catchment area. The area per year for a 10-year development period is 42.5 ha (0.425 km^2), or 6.1% of the overall catchment area.

B. Development will be mostly on low or mild slopes. For example, the development plan for the Hills proposes that development be removed from the steeper areas, and some steep areas will be revegetated.

While the proportion increase for the Back Bay immediate catchment is 21%, the more relevant metric in relation to sedimentation is the increase in total source that leads to Back Bay, which is considerably lower at 2.5% increase.

The calculations above assume that development is spread evenly over a 10-year period. If development (in particular, the primary earthworks stage) occurs in a more concentrated timeframe, there could be higher sediment loads from earthworks in a given year. Even if all the earthworks from all the proposed development take place in one year, the total load to the estuary is predicted to increase by 24%. This illustrates that staging of development to spread out earthworks can smooth out the risks of sedimentation.

Earthworks controls tend to be more effective for smaller rain events than for large events. While controls can reduce sediment load from erosion by about 95% in the long term (compared with uncontrolled earthworks), they will not be as effective for large storm events. The approach to sedimentation in this report is based on an annual average approach, rather than examining individual events and event sediment deposition. Modelling in Beachlands (Yalden and Semadeni-Davies 2021) suggests that for the 10-year return interval event, sediment loads from controlled earthworks are more like 15 times the undeveloped yield, rather than 10 times for mean annual load, although supporting field measurements are not available.

The above calculations assume that there are high-quality erosion controls. It is important that these are implemented, because poorly-controlled earthworks can release much greater amounts of sediment than well-controlled earthworks.

It is also important to protect steeper slopes (e.g., >9 degrees) from bulk earthworks, because they are more erosion-prone.

3.4 Estuary sedimentation

3.4.1 Current conditions

Estimated sediment deposition depths associated with the mean annual sediment load are shown in Table 3-11.

Table 3-11: Sedimentation rates associated with mean annual catchment sediment load, assessed for current climate conditions and land use, for the high deposition scenario.

Compartment name	Area (km^2)	Non-channel area (km^2)	Sediment source from compartment catchment (t/year)	Deposition rate Low estimate (mm/year)	Deposition rate High estimate (mm/year)
Southern Arm	0.60	0.59	1321.4	0.19	0.47
Tara Arm	0.35	0.34	1483.8	0.34	0.84
Back Bay	1.23	1.20	71.3	0.48	1.20
Mid Estuary	0.99	0.85	85.5	0.14	0.56
Lower Estuary	1.55	0.99	13.4	0.12	0.48
Mouth	0.43	0.09	21.6	0.00	0.00
Even deposition of total load	5.16	4.06	2997	0.15	0.59

Note: Area of the last row does not match the sum of the columns above due to rounding of values in the table.

These results indicate that most of the areas have a deposition rate of less than 1 mm/year associated with the annual catchment load. Typically, 2 mm/year above background (natural) rates is indicative of potential ecological impacts of sedimentation (Townsend and Lohrer 2015). Back Bay has the highest rate of estimated sedimentation, which reaches 1.2 mm/year under the high estimate. This results from Back Bay receiving inputs from the main inputs of the Tara Arm and Southern Arm, and that bay is likely to capture a considerable proportion of the sediment sources from the catchment of those arms.

Importantly, this assessment does not account for redistribution of sediment within the estuary following initial deposition. Redistribution can result in increases in long term deposition in some areas (low-energy areas and mangrove fringes), and reduction of sediment deposition rates in the in some locations (even net erosion).

The assessment also assumes that sediment is spread evenly over the non-channel part of the sub-estuary. In reality, sedimentation may be more focussed in some parts of the sub-estuary.

Nuisance muddy sediment deposits in flats beside Lincoln St were observed following storms in February 2023 (community knowledge, relayed by Phil McDermott). But as of September 2024, there is little sign of this, nor over the body of Back Bay (personal observation). A coarse estimate of sediment sources from Cyclone Gabrielle (around 12 February 2023) can be obtained as follows. Cyclone Gabrielle had an event rainfall of 198 mm according to the NIWA Virtual Climate Station Network (VCSN). This rainfall is equivalent to a 30-year ARI (Average Recurrence Interval) 48-hour event according to the NIWA HIRDS (https://hirds.niwa.co.nz/) tool. The VCSN record over the last 40 years show that similar sized events occurred in 1998, 2007 and 2011 (with none significantly larger), suggesting an ARI for Cyclone Gabrielle closer to 10 years.

Typically, 10-year return interval storms deliver about the mean annual sediment load, and the 30 year return interval storm delivers about 2.5 times the mean annual load (author's unpublished analysis based on sites around New Zealand; see alsoHicks 1994). Based on the 30-year value, a modelled deposition depth would be about 1.2 mm for the lower estuary for the high deposition scenario, which might have resulted in some thin deposits of mud that would be noticeable. In contrast, estuaries on the east coast of the Coromandel Peninsula had thick deposits in places for the February storms, suggesting that Mangawhai is less deposition-prone than those estuaries. This area is also subject to currents, shallow wind waves, and bioturbation, with erosion-prone shoreline, suggesting that long-term accumulation is unlikely. During this event, there may also have been redistribution of sediment, resulting in localised deposition of silt and fine sand, as observed in some locations such as near the Pearson St Reserve (Mangawhai Matters Inc. 2023).

The 30-year event could also lead to 3.6 mm deposition in Back Bay for the high deposition scenario. Single-event deposition of 3 mm of terrestrial sediment can alter benthic biota communities on estuary flats in New Zealand (Lohrer et al. 2004), although this impact would be infrequent. Informal inspection of Back Bay in September 2024 did not show evidence of deposits from Cyclone Gabrielle (which had a return interval of >10 years), which suggests that the deposition estimate is high or that the estuary had recovered. It is unclear how well sediment deposited in Back Bay will remobilise. Clearly there has been accretion in the past, giving rise to mangrove proliferations, some of which have been removed. However, the sediment in the body of Back Bay is not muddy, suggesting that fine sediment (mud) is not deposited there, or that deposited fine sediment is later remobilised. A similar situation applies for the area in front of the Insley St causeway.

The Tara and Southern arms have historically seen expansion of mangroves, which is usually associated with sediment deposition. Reviewing of historical images in RetroLens shows that before causeway construction (in the 1960s for Insley St causeway and 1970s for the Molesworth Dr causeway across Tara Creek) there were much fewer mangroves (Mangawhai Matters Inc. 2023). Sediment deposition and mangrove expansion could well be associated with flow restrictions associated with the causeway. Ongoing accretion upstream of the causeways is unlikely given that non-channel areas are elevated (and hence not inundated for long), areas in the back of mangroves generally see lower deposition rates and the area is largely infilled. On the other hand, relative sea level rise will increase the accommodation volume, and mangrove fringes can be effective in trapping sediment.

3.4.2 Climate change

The estimated sedimentation rate from the mean annual load (obtained by spreading proportions of annual catchment loading over sub-estuaries) for the high sedimentation estimate under various climate related temperature increase is shown in Table 3-12. Large increases in summer temperature (3 °C above current) are predicted to increase sediment deposition by 63%. The corresponding predicted deposition rate is 1.97 mm/year in Back Bay for the high deposition scenario. This almost equals to the ecological effects threshold of 2 mm/year.

This can be compared with relative sea level rise. The projected sea level rise in relation to the land for the SSP3-7.0 emission scenario is an average of 11 mm/year to the year 2090[15]. Hence changes in estuary water depth are likely to be dominated by relative sea level rise (and other coastal processes

[15] 0.7 m rise from 2024 to 2090.Values from https://searise.takiwa.co/map at the estuary mouth. Median-confidence value. Includes effects of vertical land movement.

such as channel migration, ingress of sediment from the coast or the dunes) rather than sediment deposition from the catchment.

Table 3-12: Estimated sedimentation rate (mm/year) associated with catchment storm inputs for the high estimate for various climate-related temperature increases.

Compartment	Increase in summer temperature			
	0°C	1°C	2°C	3°C
Southern Arm	0.45	0.54	0.64	0.73
Tara Arm	0.87	1.06	1.24	1.42
Back Bay	1.21	1.46	1.71	1.97
Mid Estuary	0.28	0.34	0.40	0.45
Lower Estuary	0.24	0.29	0.34	0.39
Mouth	0.00	0.00	0.00	0.00
Even deposition of total load	0.59	0.71	0.84	0.96

3.4.3 Future land use

The change in sedimentation based on addition of sediment associated with urban earthworks for the high-deposition scenario (using the loads from Table 3-10) is shown in Table 3-13. The predicted additional sedimentation rate associated with earthworks is small (2.8% or less increase). The underlying reasons are discussed in Section 3.3.2.

Table 3-13: Change in sedimentation associated with urban earthworks.

Estuary compartment	Sedimentation without earthworks (mm/year)	Percent increase from earthworks sediment load
Southern Arm	0.47	1.5%
Tara Arm	0.87	2.8%
Back Bay	1.23	2.7%
Mid Estuary	0.57	2.6%
Lower Estuary	0.49	2.5%
Mouth	0.00	-
Even deposition of total load	0.61	2.5%

This deposition assumes that the anticipated urban development, and the associated earthworks, will progress steadily over a 10-year period. There is a chance that urbanisation could proceed in a surge, in which case there would be a larger area of earthworks in one year, which would increase the risk of deposition. For example, compacting urban development into a 5-year period would double the increase in sedimentation associated with urban earthworks (to something like a 5.4% increase in Back Bay). Furthermore, if this development coincided with a large storm, there could be a pulse of sediment. For example, a 30-year event could increase sediment sources by a factor of 3, and erosion controls would be less effective in such a large storm, perhaps adding a factor of 2 to the load (see discussion in Section 3.4.1), leading to a factor of 6 increase in earthworks-related sediment load. When compounded with a shortened period of development, this scenario could result in a

32% increase in sedimentation in Back Bay (for example), compared with long-term average loads with no earthworks (but also bearing in mind that non-earthworks sedimentation would also increase in this infrequent event). This risk of a large event arising during a shortened period of earthworks would be offset by the chance that the earthworks could coincide with a relatively calm weather period. The balance of risks could be addressed with a more complete risk analysis (in a probabilistic framework), which has not been done in this project.

3.5 Estuary eutrophication

As discussed in Section 3.3.1, anticipated increases in TN load in the future are likely to be small or negative, unless there is widespread introduction of intensive agriculture, so here we only assess eutrophication risks for the current land use.

3.5.1 Current land use - Macroalgae

For the current scenario, the potential TN concentration was calculated as 173 mg/m^3. Hence, the predicted concentration is just within the A band for macroalgae. This indicates a low risk of macroalgal blooms, although not pristine conditions

Descriptions of the bands (from Plew et al. 2020) in relation to macroalgae are:

A: Algal cover < 5% and low biomass of opportunistic macroalgal blooms and with no growth of algae in the underlying sediment.

B: Limited macroalgal cover (5–20%) and low biomass of opportunistic macroalgal blooms and with no growth of algae in the underlying sediment. Sediment quality transitional.

From personal observation (Sandy Elliott, Phil McDermott) there are no conspicuous macroalgal growths in the estuary. Note that the ETI assessment is designed to be on the 'safe' side, to avoid mistakenly under-predicting risks.

Also, the estimated catchment loading may be too high in relation to reality, based on comparisons between estimated and measured concentrations (see Table 3-4). If loads were reduced by 25%, the potential concentration would be decreased to 140 mg/m^3, well within the A band. Overall, the risk for macroalgal growth is small.

3.5.2 Current land use - Phytoplankton

The estuary has a predicted flushing time of 12.5 days at summer mean flow, and the predicted bloom chl-a concentration is 8 mg/m^3, which would be in the B-band for phytoplankton (the A/B cutoff of 5 mg/m^3, B/C cutoff of 10 mg/m^3). However, this is likely to be conservative because:

- Phytoplankton blooms are not normally the main type of eutrophication in shallow intertidally dominated estuaries.
- Mangawhai Harbour is well flushed. It has a relatively high tidal prism proportion (67% of estuary volume empties each tide).
- It is fairly shallow and is unlikely to have strong stratification.
- The model for periphyton is based on optimal growing conditions, which may seldom be realised.

- Even if chl-a becomes elevated, effects on dissolved oxygen and light attenuation are unlikely, for the reasons above.

Overall, the susceptibility to phytoplankton and its effects of depleted oxygen and light blocking is considered to be low.

3.5.3 Future land use

Given that there are low current risks of eutrophication (see Section 2.6) and anticipated future changes in nutrient loading are expected to be minor, there is not a significant concern in relation to future estuary eutrophication.

A hypothetical unlikely but cautionary scenario is introduction of 500 ha of nutrient-intensive horticulture which could double nutrient loads to the estuary. This would increase potential N from 173 mg/m^3 to 336 mg/m^3, moving macroalgal grading into the border between B and C grades. This is unlikely because there are not widespread suitable soils, and there is also competition for use of land for lifestyle blocks.

3.6 Recommendations for further work

One key area of uncertainty is the fate of sediment that enters the estuary. While sedimentation risks were assessed as being low or moderate currently, there has historically been accretion of sediment in parts of the upper estuary. Detailed hydrodynamic and sediment transport modelling in the estuary would give insight into sediment movement patterns, including sediment redistribution, to give confirmation of the anticipated patterns. Sediment coring in critical locations could give insight into historical and current long-term sediment accumulation rates. Tracer studies could give insight into the provenance of deposited sediment. There are precedents for doing such work in other estuaries around New Zealand, but the resourcing requirements are considerably larger than for the screening analysis of this project.

4 Acknowledgements

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5 Glossary of abbreviations and terms

CLUES	Catchment Land Use for Environmental Sustainability
CMIP6	Coupled Model Intercomparison Project
DEM	Digital Elevation Model
DOC	Department of Conservation
ETI	Estuarine Tropic Indicator
HEL	Highly Erodible Land
HIRDS	High Intensity Rainfall Distribution System
LCDB	Land Cover DataBase
LINZ	Land Information New Zealand
LRI	Land Resources Inventory
MMI	Mangawhai Matters Incorporated
MWLR	Manaaki Whenua Landcare Research
NZEEM	New Zealand Empirical Erosion Model
NZSYE	New Zealand Sediment Yield Estimator
REC	River Environments Classification
SOE	State of the Environment
SSP	Shared Socioeconomic Pathway
TN	Total Nitrogen
TP	Total Phosphorus
VCSN	Virtual Climate Station Network
VLM	Vertical Land Movement

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Appendix A Summer temperature increase for Whangarei from CMIP5

These data were obtained from https://ofcnz.niwa.co.nz/#/localCharts. RCPs are Representative Concentration Pathways.

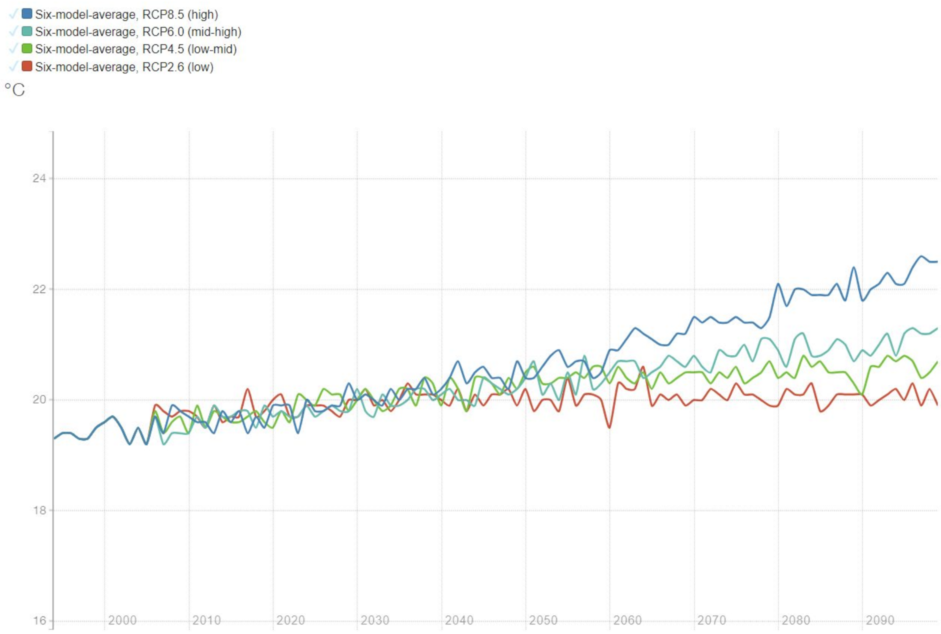

Figure A-1: Summer mean temperature for Whangarei over time for CMIP5 for three climate scenarios, averaged over 6 models.

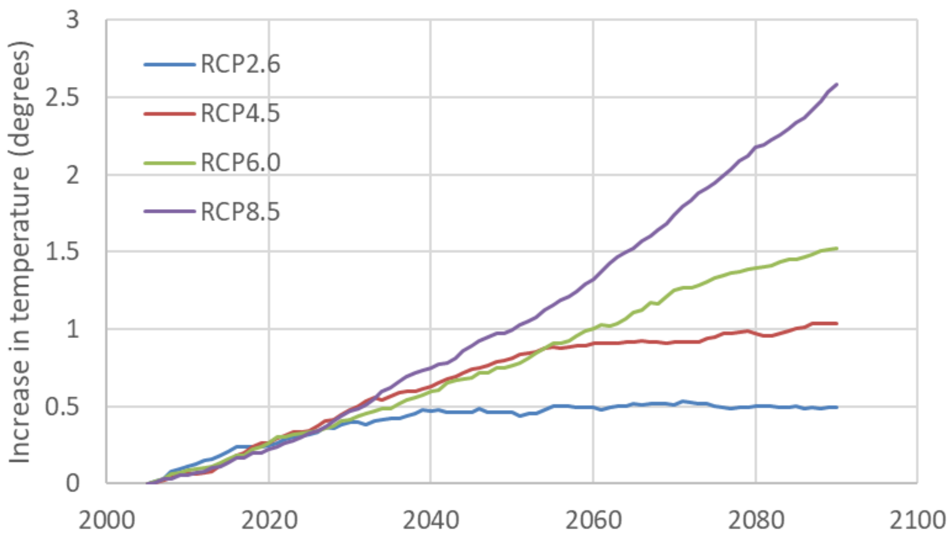

Figure A-2: Increase in summer temperature from 1995-2014 baseline for averaged over six downscaled CMP5 models. The temperature values are based on 20-year moving averages around the time on the horizontal axis.