Modelling the susceptibility of estuaries to nutrient and sediment inputs in Auckland / Tāmaki Makaurau

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Auckland Council require an analytical framework to inform the limit setting process with respect to water quality of fresh water flowing to estuaries. To establish relationships between contaminant loads (nutrients and sediments) and impacts to Auckland's estuaries, Auckland Council require information on current nutrient and sediment loads at both the estuary scale and at scales relevant to freshwater management (i.e., sub-estuaries of the larger Kaipara, Manukau and Waitematā Harbours and Tāmaki Estuary).

Sediment loads were estimated using an existing NIWA sediment loading model to provide areal sediment loads to the estuaries. Mean annual nutrient loads (total nitrogen and total phosphorus were estimated using CLUES (Catchment Landuse for Environmental Sustainability model) or statistical models (available via NZRiverMaps). Estuary Trophic Index (ETI) models were then used to predict nutrient concentrations in the estuaries, the susceptibility of estuaries to nutrient loading from land, and their consequent ecological condition. Small estuaries in the region were assessed using a 'whole of estuary' approach, as were sub-estuaries within the four major estuaries in the Auckland region (Manukau, Kaipara, Waitematā and Tāmaki). For these larger estuaries, nutrient concentrations were calculated at sub-estuary scales using existing hydrodynamic numerical models available to NIWA with tracer modelling techniques.

With a few exceptions, sediment load results showed that Auckland region estuary loads were often near to or less than the median for sediment load results nationally. The 'whole of estuary' methods using the ETI to determine susceptibility to eutrophication and ecological state indicated that most estuaries in the Auckland region are likely to be in good condition. The ETI methods gave imprecise estimates of nutrient conditions in Auckland's major estuaries, which contain large sub-estuary systems. Hydrodynamic models highlighted the localised impacts of riverine inputs from some catchments on the estuary arms they flow to. The hydrodynamic models now provide an appropriate method to assess the effects of changes in nutrient loads to Auckland's larger estuaries.

A limitation of the methods of assessing nutrient concentrations and eutrophication risk in this study is that they use 'steady-state' nutrient load estimates based on NIWA's Catchment Land Use for Environmental Sustainability (CLUES) and NZ River Maps models. Auckland Council's Freshwater Management Tool (FWMT) should provide a suitable tool to depart from this 'steady state' assessment and provide a means to incorporate changes in nutrient load through time into the modelling. However, this work noted that modification of the FWMT would be needed for its use to extend to estuary management, particularly to include parts of estuary catchments not currently covered by this model.

To improve the accuracy of the modelling approaches used in this study, we recommend extending Auckland's water quality monitoring network to monitor contaminant concentrations and flow rates at terminal river reaches flowing to estuaries, along with maintaining a good understanding of nutrient concentrations in coastal oceanic water in the Auckland region.

Gathering more information to better calibrate ETI predictions for northern New Zealand is also recommended. We recommend that our estimates of ecological impact from contaminant loads to Auckland estuaries are used only as guides for regional quantification of relationships between loads and responses of estuary attributes. This regional quantification is vital to assess the ecological consequences to estuaries and sub-estuaries in the Auckland region resulting from changes in nutrient concentration. It is notable that current eutrophication risk for Auckland estuaries is generally low relative to estuaries nationally (including estuaries in Northland). For this reason, we recommend that Auckland Council scientists consider collaboration with other northern councils (where some estuaries have higher eutrophication risk) when developing nutrient targets for estuaries.

1 Introduction

1.1 Background

Auckland Council require an analytical framework to inform the limit setting process with respect to water quality of fresh water flowing to estuaries. To establish relationships between contaminant loads (nutrients and sediments) and impacts to Auckland's estuaries, Auckland Council requires information on nutrient and sediment effects at both the whole estuary/harbour scale and at scales relevant to freshwater management (i.e., sub-estuaries of the larger Kaipara, Manukau and Waitematā Harbours). Specific information and guidance are required on:

1. baseline state[1] and current catchment nutrient loads delivered to (sub)estuaries in the Auckland region.
2. sediment loading rates for (sub)estuaries in the Auckland region.
3. estuary nutrient concentrations corresponding to baseline state (and target) freshwater loads.
4. which parts of the (sub)estuaries are exposed to the highest nutrient concentrations.
5. whether primary production (and hence eutrophication symptoms) in estuaries in the Auckland region are likely to be controlled by phosphorus from land.
6. which estuaries and sub-estuaries in Auckland are most susceptible to eutrophication (given their geomorphology, hydrodynamics and nutrient loads) and therefore need the most stringent freshwater nutrient targets.
7. the ecological consequences to estuaries and sub-estuaries in the Auckland region resulting from changes in nutrient concentrations.
8. whether proposed nutrient targets in streams and rivers will safeguard against eutrophication in receiving estuaries.
9. whether the nitrogen criteria from ETI Tool 1 are suitable for (sub)estuaries in Auckland; and what revisions, if any, would need to be made for the Auckland context.

This project provides information specifically addressing points 1–7 in the list above. This information will also inform the direction of future research to better address point 6 and 7, and to address points 8 and 9.

With regard to management of coastal environments, Auckland Council is responsible for meeting the requirements of the National Policy Statement for Freshwater Management (NPS-FM). Specifically, with regard to contaminant loads from rivers, the NPS-FM requires Auckland Council to *identify and consider 'nutrient sensitive' coastal receiving environments*[2]*.* In addition, in future there may be other requirements to monitor estuaries; the draft National Planning Framework (Ministry for the Environment, 2023) compulsory estuary attributes included nuisance macroalgae and

[1]Auckland Council must identify the 'baseline attribute state' (BAS) for all nationally compulsory attributes (i.e., those in NPS-FM 2020 Appendices 2A and 2B), as well as for any other attributes the Council identifies for use in the region. This requirement to identify BAS is laid out prescriptively in NPS-FM clause 3.10. Identifying BAS is a necessary step to then setting 'target attribute states' under clause 3.11. Auckland Council has interpreted the various relevant clauses (3.10, 1.4 and 1.6) to understand that BAS means using the best information available to estimate the state of the attribute on 7 September 2017.

[2] NPS-FM (2020) cl 3.13 Special provisions for attributes affected by nutrients.

seagrass extent. These attributes are dependent on eutrophication and sedimentation processes within estuaries.

To manage the impacts of contaminants from land on aquatic environments, Auckland Council and other regional government authorities are moving towards integrated catchment management strategies that includes estuaries.

In response to the requirements of the NPS-FM (2014), in 2017 regional council coastal scientists sought advice via the coastal Special Interest Group (cSIG), with funding through Envirolink Tools Grant (Contract No. C01X1420), for the development of a nationally consistent approach to assessment of estuary eutrophication, and threshold bands for contaminant (nutrient and sediment) loading from land. The purpose of that project, called the NZ Estuary Trophic Index (ETI), was to assist regional councils in determining the susceptibility of estuaries to eutrophication (ETI Tool 1), assess current trophic state of estuaries (Robertson, Stevens et al. 2016) and assess how changes to nutrient and sediment loads may alter estuary ecological state (Zeldis and Plew 2022).

ETI Tool 1 predicts nutrient concentrations in New Zealand coastal waters by combining estimates of nutrient loads from catchments with simple estuary dilution models that determine the freshwater flushing and mixing of ocean- and river- water in estuaries. The tool chooses the appropriate dilution model to use based on estuary volume, tidal prism and freshwater inflow, calculates estuary nutrient concentrations, and assesses them with respect to eutrophication susceptibility bands (Plew et al. 2020).

To meet Auckland Council requirements, some additional consideration of estuary characteristics present in the Auckland region was needed. These characteristics include:

1. Estuaries in the Auckland region are large and have coastlines and river inputs that are comprised of many catchments. For Auckland Council to complete management strategies for each of these catchments it is necessary to divide large estuaries in the Auckland region into sub-estuaries for eutrophication susceptibility assessments. This has not been done in national-scale ETI work to date.

2. Most estuaries in New Zealand's northern regions (Waikato, Auckland, and Northland) contain mangroves. The ecological data behind ETI eutrophication susceptibility bands are derived from areas of New Zealand outside these regions. Mangroves provide shade, stabilise sediments, take up nutrients, as well as other ecological effects likely to alter relationships between contaminant loading rates and impacts (including to macroalgae and seagrass cover) in New Zealand's northern estuaries. For these reasons the ETI Tools may currently be less accurate in estuaries that contain mangroves.

1.2 Scope

In this project, NIWA has prepared ETI models for estuaries in the Auckland region. We have considered both individual estuaries, that are assessed using a 'whole of estuary' approach, and sub-estuaries within four major estuaries in the Auckland region (Manukau, Kaipara, Waitematā and Tāmaki). These models can be used to predict the effects of different nutrient loads on estuaries or sub-estuaries. The response to nutrient loads is based on the ETI approach and its source data. We also calculate areal sediment loading rates to each of the listed estuaries. A detailed scope is as follows:

- Review the measured estuary water quality monitoring data available from Auckland Council (and Northland Regional Council if appropriate) for its suitability in validating models where required.
- Review the four available sources of data available for contaminant loads to estuaries: measured data (SOE monitoring), NIWA’s Catchment Land Use for Environmental Sustainability (CLUES) model (Elliott, Semadeni-Davies et al. 2016), New Zealand River Maps (Whitehead and Booker 2019, Whitehead, Fraser et al. 2022) data, or Auckland Council's Freshwater Management Tool (FWMT v1.2.1), and compare the likely utility of these data sources. The aim for this step is to assess if data from each of these sources are sufficiently accurate to answer the questions listed in section 1.1. We note that AC has specified that if appropriate data are available via FWMT, this data source would be preferred, as the FWMT provides inbuilt management scenarios that can be used to model the impact of various interventions on loads.
- Based on the review described in the point above, provide brief recommendations on where additional freshwater and estuarine monitoring sites may be required to track improvements to freshwater and coastal water quality.
- Model ‘potential’ nutrient concentrations (N and P) in estuaries across Auckland using the most accurate available catchment nutrient loads (whether from CLUES, FWMT or measured data). Potential nutrient concentrations are obtained by treating nutrients as conservative tracers in calculations of dispersal and mixing. Unless otherwise specified, estuaries to be assessed will be those within the Auckland region listed in NIWA’s Coastal Explorer Database. (Table 1-1). These data will be updated from more recent studies and data held by NIWA, where available.
- For the Kaipara, Manukau and Waitematā Harbours, and Tāmaki Estuary, model nutrient concentrations at sub-estuary scales using existing numerical models available to NIWA. Sub-estuaries are as listed in Table 1-2. Boundaries for these sub-estuaries will follow those provided by Auckland Council to NIWA by email on 9/09/23. This modelling will be conducted using median flows from rivers flowing to each estuary.
- Employ ETI tools 1 and 3 to provide predictions of susceptibility and ecological state to eutrophication for each (sub)estuary under current and alternative load scenarios.
- Calculate sediment loading rates for estuaries and sub-estuaries as listed in Table 1-1 and Table 1-2.

Table 1-1: List of stand-alone estuaries in the Auckland region to be included in this study. Single compartment dilution models will be used to estimate nutrient concentrations and eutrophic susceptibilities of these estuaries. Locations of these estuaries can be seen via [Coastal Explorer (arcgis.com)]().

Names of stand-alone estuaries		
Pakiri River	Mangemangeroa Estuary	Te Matuku Bay
Omaha Cove	Turanga Creek	Awaawaroa Bay
Whangateau Harbour	Waikopua Creek	Rocky Bay
Millon Bay	Wairoa River	Putiki Bay
Matakana River	Waitakere River (Bethells Beach)	Huruhi Bay
Mahurangi Harbour System	North Cove	Tryphena Harbour
Te Muri-O-Tarariki	Bon Accord Harbour	Blind Bay
Puhoi River	South Cove Harbour	Whangaparapara Harbour
Waiwera River	Gardiner Gap	Port Fitzroy/Port Abercrombie
Orewa River	Islington Bay	Katherine Bay
Okoromai Bay	Matiatia Bay	Rangiwhakaea Bay
Hobbs Bay (Gulf Harbour)	Owhanake Bay	Whangapoua Creek
Weiti River	Oneroa Bay	Awana Bay
Okura River	Mawhitipana Bay	Kaitoke Creek

Table 1-2: Sub-estuaries or regions to be resolved within larger estuary systems. Existing hydrodynamic models will be used for the large estuaries, with results extracted from the models for each sub-estuary.

Estuary	Sub-estuary
Manukau Harbour System (MHS)	Manukau proper
	Māngere Inlet
	Puhinui Creek
	Pahurehure Inlet
	Clarks Creek
	Taihiki River
	Waiuku River
	Pukaki/Waokauri Creeks
Waitematā Harbour System	Upper Waitematā
	Rangitopuni Creek
	Brigham Creek
	Rawawaru Creek
	Paremoremo Creek
	Lucas Creek

Estuary	Sub-estuary
	Hellyers Creek
	Waiarohia Inlet
	Central Waitematā
	Henderson Creek
	Whau Estuary
	Hobson Bay
Tāmaki	Lower Tāmaki
	Upper Tāmaki
Kaipara	Central Kaipara South
	Tauhoa Estuary
	Hoteo River
	Makarau Estuary
	Southern/Shelly Beach compartment

Longer-term research will be needed to develop nutrient load and concentration criteria (thresholds) suitable for Auckland, and to provide the guidance to better address point 6, and to address points 7-9 in section 1.1, above. Such research is not within the scope of the current project but would include the following.

- Consider effects of mangroves on relationships between estuary nutrient concentrations and target attributes for estuaries in the Auckland region.
- Monitor indicators of nutrient enrichment (e.g., macroalgae, bottom water dissolved oxygen, porewater nutrients, redox potential depth (RPD)) in locations modelled to have low, moderate and high susceptibility to eutrophication.
- Elucidate relationship between catchment nutrient loads, estuary nutrient concentrations and estuary attributes such as nuisance macroalgae and seagrass extent through targeted monitoring projects.
- Develop an understanding of the influence of climate cycles and multiple stressors on estuary attributes.

2 Methods

2.1 Overview

Eutrophication is the process by which water bodies become enriched with nutrients, stimulating the excessive growth of primary producers. In estuaries, eutrophication is commonly expressed through growth of nuisance macroalgae and/or microalgae (phytoplankton). Under eutrophication, excess algal growth leads to detrimental consequences in estuaries that include loss of seagrass, reductions in water clarity, reduced invertebrate diversity, reduced dissolved oxygen, and changes in sediment chemistry including changes in oxygen penetration and increased nitrogen/carbon (organic matter) content. These changes can be considered 'secondary indicators' of eutrophication.

Here we use the ETI tools to make whole-of-estuary predictions of susceptibility to blooms of nuisance macroalgae and phytoplankton based on estuary dilution characteristics and nutrient load, and ETI Tool 3 to score the health of the estuary. This whole-of-estuary approach provides no spatial resolution, so is best suited to smaller estuaries. The data underpinning these tools come largely from New Zealand intertidally dominated lagoonal estuaries and to a lesser extent, riverine estuaries, in the South Island.

The second approach, applied to large estuaries (Kaipara, Manukau, Waitematā and Tāmaki), is to use hydrodynamic models which simulate the transport and mixing of tracers released from streams that discharge into the estuaries. The tracers are used to estimate the likely concentration of nutrients in the estuary. This approach can give both spatial and temporal resolution, but in this study, we consider only spatial variability using time-averaged conditions.

2.2 Water quality and flow data processing and analysis

2.2.1 Estuary monitoring data

Estuary monitoring data from sites within the Manukau, Waitematā and Kaipara harbours were provided by Auckland Council for comparison to modelled nutrient concentrations. We extracted total nitrogen (TN) and total phosphorus (TP) data and calculated mean concentrations for each site. Because some sites had data records spanning several decades, we compared means for sites calculated across all dates (full data record) to means calculated for 01/01/2009 to 01/01/2018 (reduced data record) - a period leading up to and slightly beyond the baseline attribute state date in late 2017. Across all estuarine monitoring sites, means for both TN and TP calculated using the full data record sat close to the 1:1 line with means calculated using the reduced data record. We used means calculated from 2009 onwards in all comparisons.

2.2.2 Freshwater load comparisons

We compared available model estimates of loads of nutrients to Auckland estuaries in two ways. First, we compared loads estimated at upstream freshwater monitoring sites (SoE site comparison). We selected sites that had measured time series of flow and nutrient (TN and TP) concentrations. At these sites we calculated 'measured' daily load by multiplying the TN (or TP) concentration by the flow measured on a given day, and 'measured' annual load by taking the average measured daily load for the year, multiplied by 365. We compared these 'measured' loads to modelled loads for each river site from the CLUES model, and 'NZRiverMaps loads'. Data from the FWMT database were not available for this SoE site comparison.

We also compared estimated loads for the three models (FWMT, CLUES and NZRiverMaps) at terminal reaches entering each estuary in the Auckland region. This comparison did not involve measurements of concentrations or flows as no monitoring data were available from terminal river reaches.

Loads from CLUES were calculated on 3 March 2022 using CLUES Pro under a project for the Ministry for the Environment (Semadeni-Davies, Elliott et al. 2021). This version of CLUES used a national calibration (Elliot et al. 2016; Semadeni-Davies et al. 2019; Semadeni-Davies et al. 2020) except for Northland, where a regional calibration was used. The model was calibrated to observations from the period January 2006 to December 2010.

Loads from NZRiverMaps were estimated by multiplying median nutrient concentrations by mean flow estimates from the NZRiverMaps database (Whitehead and Booker 2019). The modelled median concentrations are predicted by "random forest modelling", relating geography & topology, climate & flow, geology, land cover, and land use intensity to water quality observations. The model is calibrated to data collected from 2016 to 2020 (Whitehead, Fraser et al., 2022).

2.2.3 Sediment load data

Sediment loads for all terminal reaches connecting to estuaries in the Auckland region were obtained from the updated sediment load estimator for New Zealand described by Hicks, Semadeni-Davies et al. (2019). Loads were summed for each estuary, or estuary zone for the Manukau, Kaipara, Waitematā and Tāmaki.

The sediment load estimator is calibrated nationally against river mean annual suspended sediment loads from 273 monitoring sites collected between 1957 through to 2015. This broad timespan inevitably captures some variability/change in climate and change in catchment land cover. To mitigate this, Hicks et al. (2019) used (i) the most up to date estimates of sediment loads where revised estimates were available, (ii) 30–year–averaged 1981–2010 rainfall normal maps, and (iii) the 2008 Land Cover Database v3. We note that the sediment yield estimator predicts 'contemporary' sediment loads but not necessarily present–day loads. It also does not predict sediment loads from urban catchments.

2.3 ETI Tool 1 screening

ETI Tool 1[3] makes predictions of macroalgal blooms using the Ecological Quality Rating (EQR), a combined metric based on measures of cover and biomass (Water Framework Directive - United Kingdom Advisory Group 2014; Stevens, Forrest et al. 2022). Potential for macroalgal blooms is based on annual total nitrogen loads and estuary dilution characteristics. ETI Tool 1 also predicts the potential for phytoplankton blooms based on predicted total nitrogen (TN), total phosphorus (TP) and flushing time (Plew, Zeldis et al. 2020). For each estuary, an estimate of the amount of mixing between river-sourced and ocean-sourced waters are made using a modified tidal prism model (Plew, Zeldis et al. 2018). This model uses tidal prism (at spring tide), mean freshwater inflow, and a tuning factor that is either calculated from salinity where suitable data are available or estimated based on estuary type and the ratio of freshwater inflow over a tidal period to the tidal prism. This tuning factor accounts for return flow (a portion of the flow discharged from the water body on the ebb tide that re-enters on the flood tide), and incomplete horizontal mixing within the water body (the model assumes any substance introduced to the estuary water column is instantaneously and

[3] https://shiny.niwa.co.nz/Estuaries-Screening-Tool-1/, release date 6 Dec 2023

uniformly mixed throughout the volume of the estuary). The amount of mixing is calculated as either a dilution factor *D* or its inverse, the freshwater fraction *f*. Once the amount of mixing is known, the estuary volume- and time-averaged TN and TP concentrations are determined by scaling the concentrations from the freshwater source and ocean appropriately. For example, if the freshwater fraction was 0.2 (20% of the water in the estuary originated from rivers), then the TN concentration in the estuary would be determined as $TN_{estuary} = 0.2 \times TN_{river} + 0.8 \times TN_{ocean}$. We commonly refer to this estimate of concentration as a *potential* concentration as it does not account for other sources or losses of nutrients such as denitrification (nitrogen gas loss to the atmosphere), fluxes of nutrients between water and sediments, or uptake by primary producers. It measures the estuary concentrations of TN or TP potentially available to the primary producers, from riverine and ocean loading.

ETI Tool 1 makes predictions of both macroalgae and phytoplankton abundance. Estuary type and intertidal area are used to decide which of these primary indicators is likely to determine estuary susceptibility, when determining the overall susceptibility score. Generally, if intertidal area is >40% of total estuary area, excessive macroalgae is considered most likely to cause other deleterious effects such as impacted ecological communities and degraded sediment quality (Plew, Zeldis et al. 2020; Zeldis and Plew 2022). Water bodies with low intertidal area (<5%) tend to be deeper, have less available habitat for macroalgae, are more prone to water column stratification, and hence more likely to be impacted by high phytoplankton concentrations which may cause oxygen depletion and high light attenuation. Water bodies with intermediate intertidal area may be susceptible to effects of both forms of algal bloom.

2.3.1 Macroalgae susceptibility

Predictions of the susceptibility to eutrophication in the form of excessive growth of nuisance macroalgae are made from predicted potential TN concentrations. Macroalgal EQR has been demonstrated to decrease (worsen) with increasing potential TN in New Zealand estuaries (Plew, Zeldis et al. 2020; Stevens, Forrest et al. 2022). Potential TN concentrations corresponding to EQR bands are set based on 46 observations across 37 estuaries (Leigh Stevens – Salt Ecology, pers. comm. Feb 2023). There is considerable scatter in the relationship between potential TN and observed EQR (Figure 2-1; the dashed black line shows a least-squares fit linear regression). This is caused by several factors including the accuracy of the potential TN values due to uncertainties in both nutrient loads to catchments and the calculation of dilution in the estuaries to convert catchment nutrient loads to potential concentrations, other factors that may limit macroalgae growth (e.g., light availability, scouring, and temperature), lags between changes in nutrient loadings and macroalgal response, and errors in the field estimates of EQR. A property of a least-squares fit linear regression is that, compared to observations, there is an equal probability that a prediction made using the regression will overpredict (i.e., the actual EQR score is lower) or underpredict (i.e., the actual EQR score is higher). For assessing the susceptibility of an estuary to eutrophication, it is preferable to be conservative and predict a lower EQR score (i.e., more impact of macroalgae) than a higher EQR score. The predictor interval, calculated from the distribution of observations about the least-squares best-fit regression, is used to set nutrient concentrations corresponding to EQR bands at a level that provides a 25% under-protection risk in line with international recommendations for setting ecological relevant nutrient thresholds (Phillips, Kelly et al. 2019; Kelly, Phillips et al. 2022). For example, the C/D band threshold (EQR = 0.4) for potential TN is set at 495 mg/m^3; at this concentration, there is a 25% probability that EQR is lower (i.e., worse) than 0.4. If instead the threshold were based on where the regression fit gives an EQR = 0.4, then at that concentration (555 mg/m³) there would be a 50% probability that the EQR was lower than 0.4. Potential TN concentration bands are summarised in Table 2-1.

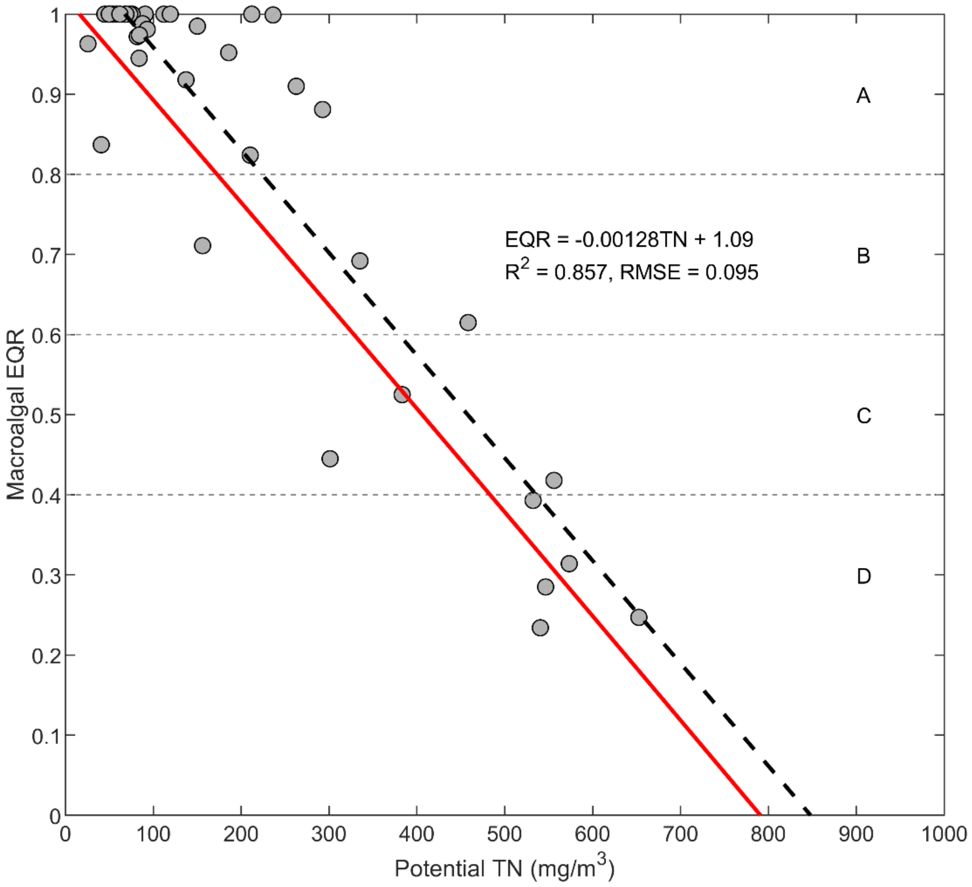

Figure 2-1: Macroalgal EQR vs potential TN relationship. The dashed black line shows a least-squares best fit linear regression through the data, while the solid red line is set at the 25% under-protection level (where 25% of observed values have worse EQR than would be predicted using this relationship).

Table 2-1: Bandings for Macroalgae using ETI Tool 1. Potential concentration levels corresponding to EQR bands are set using a 25% under-protection risk. Expected ecological state from Plew, Zeldis et al. (2020).

Macroalgae susceptibility band	A	B	C	D
Eutrophication level	Minimal	Moderate	High	Very high
Ecological Quality Rating (EQR)	1.0 > EQR ≥ 0.8	0.8 > EQR ≥ 0.6	0.6 > EQR ≥ 0.4	EQR < 0.4
Potential TN concentration (mg/m^3)	TN ≤ 175	175 < TN ≤ 335	335 < TN ≤ 495	TN > 495
Expected ecological state	Ecological communities (e.g., bird, fish, seagrass, and macroinvertebrates) are healthy and resilient. Algal cover <5% and low biomass of opportunistic macroalgal blooms and with no growth of algae in the underlying sediment. Sediment quality high	Ecological communities (e.g., bird, fish, seagrass, and macroinvertebrates) are slightly impacted by additional macroalgal growth arising from nutrients levels that are elevated. 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	Ecological communities (e.g., bird, fish, seagrass, and macroinvertebrates) are moderately to strongly impacted by macroalgae. Persistent, high % macroalgal cover (25–50%) and/or biomass, often with entrainment in sediment. Sediment quality degraded	Ecological communities (e.g., bird, fish, seagrass, and macroinvertebrates) are strongly impacted by macroalgae. Persistent very high % macroalgal cover (>75%) and/or biomass, with entrainment in sediment. Sediment quality degraded with sulfidic conditions near the sediment surface

2.3.2 Phytoplankton susceptibility

Susceptibility to phytoplankton blooms is determined from an analytical growth model using predicted summertime potential TN and TP concentrations and flushing time. This model (described by Plew, Zeldis et al. 2020) predicts the maximum likely accumulation of estuarine phytoplankton biomass as chlorophyll-*a* (chl-*a*) under conditions when nothing other than nitrogen and phosphorus availability and estuary flushing time limits growth. Thus, the model is a predictor of potential bloom conditions. The model does not consider chl-*a* originating from the ocean or delivered to the estuary in the river inflows, and only predicts chl-*a* resulting from the growth of phytoplankton in the estuary itself. Estuaries with flushing times less than the doubling time of phytoplankton (~ 3 days) are not likely to experience phytoplankton blooms as the phytoplankton is flushed from the system faster than it grows. In such cases, the model predicts zero chl-*a*, although as noted, there could be chl-*a* present in the estuary having come from the ocean or river inflows. At long flushing times (~ 1 month), predicted phytoplankton concentrations are limited only by nutrient availability. For intermediate flushing times, the likely maximum phytoplankton concentration increases with flushing time. Figure 2-2 demonstrates the predicted chl-*a* concentrations as a function of flushing time and potential TN concentration for the case where phosphorus is not limiting (although the phytoplankton model does consider both TN and TP).

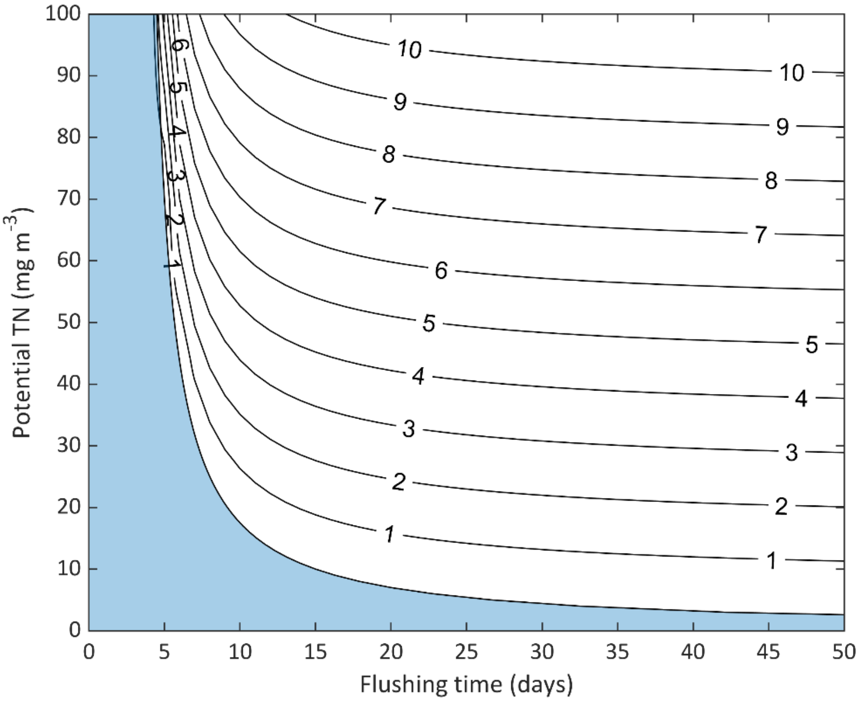

Figure 2-2: Predicted maximum phytoplankton chlorophyll-*a* (chl-*a*) as a function of potential TN and estuary flushing time. This graph shows the chl-*a* concentration resulting from phytoplankton growth in the estuary, assuming phosphorus is not limiting. The area shaded blue indicates where phytoplankton is predicted to be flushed from the estuary faster than it grows resulting in zero chl-*a*.

The predicted chl-*a* concentrations are banded based on estuary salinity, with higher chl-*a* concentrations permitted in freshwater/oligohaline systems such as coastal lakes and freshwater river mouths, and lower concentrations in euhaline systems such as coastal embayments (Plew, Zeldis et al. 2020). These susceptibility bands for phytoplankton in estuarine systems are based on those proposed for the NZ ETI (Robertson et al. 2016b). The NZ ETI bandings for scoring estuary eutrophic state for phytoplankton are largely based on response thresholds for Basque estuaries (Revilla, Franco et al. 2010) due to a lack of suitable New Zealand data. Basque estuaries are generally shallow and well drained like the majority of New Zealand estuaries. Many coastal hydrosystems are freshwater systems (e.g., coastal lakes or lagoons, so not strictly “estuarine”) or have low salinities that would suppress estuarine phytoplankton growth. For freshwater or brackish (salinity < 5 ppt) systems, we apply bandings from the New Zealand National Policy Statement for Freshwater Management for the maximum chlorophyll-*a* concentrations in lakes (Ministry for the Environment 2018).

Table 2-2: ETI bands for chlorophyll-*a* (chl-*a*). The bandings for chl-*a* differ depending on the characteristic salinity of the hydrosystem. Susceptibility bands and expected ecological state from Plew, Zeldis et al. (2020).

Phytoplankton susceptibility band	A	B	C	D
Eutrophication level	Minimal	Moderate	High	Very high
Euhaline (>30 ppt)	chl-*a* ≤ 3 µg/L	3 < chl-*a* ≤ 8 µg/L	8 < chl-*a* ≤ 12 µg/L	chl-*a* > 12 µg/L
Meso/polyhaline (≥5 30 ppt)	chl-*a* ≤ 5 µg/L	5 < chl-*a* ≤ 10 µg/L	10 < chl-*a* ≤ 16 µg/L	chl-*a* > 16 µg/L
Oligohaline or fresh water (<5 ppt)	chl-*a* ≤ 10 µg/L	10 < chl-*a* ≤ 25 µg/L	25 < chl-*a* ≤ 60 µg/L	chl-*a* > 60 µg/L
Expected ecological state	Ecological communities are healthy and resilient. high	Ecological communities are slightly impacted by additional phytoplankton growth arising from nutrients levels that are elevated.	Ecological communities are moderately impacted by phytoplankton biomass elevated well above natural conditions. Reduced water clarity likely to affect habitat available for native macrophytes.	Excessive algal growth making ecological communities at high risk of undergoing a regime shift to a persistent, degraded state without macrophyte/seagrass cover.

2.4 ETI Tool 3 screening

ETI Tool 3 is a Bayesian Belief Network (BBN) model that predicts an ETI score ranging between 0 (no symptoms of eutrophication) to 1 (grossly eutrophic) (Zeldis and Plew 2022). The BBN is designed for shallow tidal lagoons, tidal river estuaries and coastal lakes. It is driven by estuary physiographic characteristics (estuary type, flushing time, intertidal area, estuary closure state, water column stratification) and nutrient and sediment loads. Much of these data are available from running ETI Tool 1. The model predicts responses of primary indicators (macroalgae and phytoplankton biomass) and secondary indicators (or symptoms) of estuary ecological impairment (sediment carbon, sediment apparent redox potential discontinuity depth, water column oxygen, macrobenthos and seagrass condition) to nutrient and sediment loads. Relationships between nodes of the BBN (Figure 2-3) are based primarily on observational and model-based information from New Zealand and international studies. A full description of the BBN is given by Zeldis and Plew (2022), with modifications to the macroalgae, apparent redox potential discontinuity (aRPD) depth, seagrass, and macrobenthos nodes described by Hale, Zeldis et al. (2024).

The BBN makes predictions of measurable indicator variables (for example, sediment total organic carbon content as a %, apparent redox potential discontinuity depth in cm). The exception is for seagrass decline, which is banded in a narrative fashion from minor to extreme. This is because it is often difficult to define the natural extent of seagrass beds from which to calculate a reduction in cover or biomass. Decline in seagrass is predicted from macroalgae and sedimentation, with high macroalgal biomass and high sediment accumulation rates associated with greater decline in seagrass (Hale, Zeldis et al. 2024). An extreme decline would indicate a near-total loss of seagrass, typically associated with sediment accumulation rates > 10 mm y^{-1}. Sediment accumulation rates < 5 mm y^{-1} are assumed to have negligible effects, and moderate to severe effects from 5 to 10 mm y^{-1}.

Macroalgal EQR interacts with sedimentation in negatively impacting seagrass, with worsening effects of sedimentation occurring at EQR values below 0.6 (Hale, Zeldis et al. 2024).

Predicted values for BBN indicators are then standardised and banded A to D, akin to the National Objective Framework (NOF) attribute bandings used in the NPS-FM. Note that NOF attributes have not been set for estuaries at the time of preparing this report. The standardised primary and secondary indicators BBN scores are used to calculate the ETI score and band. The bandings applied to each indicator are described in Table 2-3. A feature of the BBN is that it is probabilistic and gives the probability distribution for the band of each indicator as well as the overall ETI score.

In this study, the BBN is used in a purely predictive manner, using only the physiographic drivers and nutrient/sediment loads to predict ecological condition. However, refined predictions can be made by using field-derived observations of indicator values to reduce the uncertainty associated with the probabilistic BBN score (as done by Hale, Zeldis et al. (2024).

The ETI Tool 3 BBN was developed for tidal lagoons, tidal rivers, and coastal lakes. Several of the estuaries in the Auckland region are classified as coastal embayments or shallow drowned valleys. These have been modelled as tidal lagoons. Beach streams are modelled as tidal rivers. Estuaries with mean depth greater than 5 m are assumed to be stratified, and shallower estuaries not stratified.

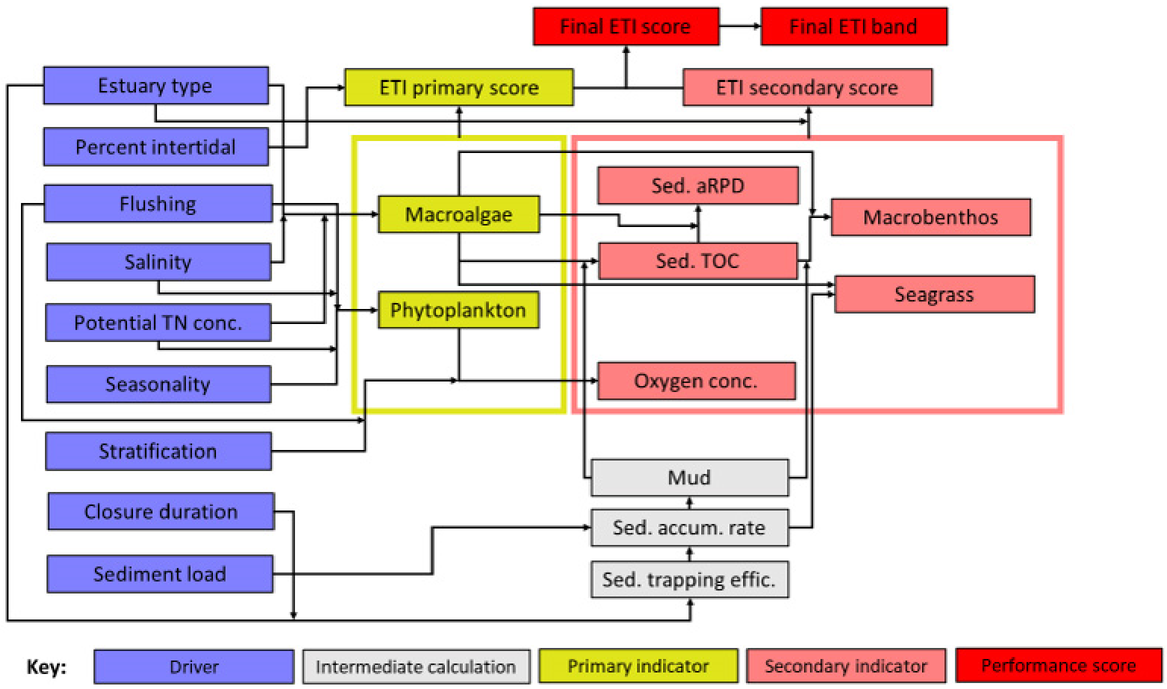

Figure 2-3: Schematic of the ETI Tool 3 BBN. Information on 'drivers' (blue nodes) are input by the user and the BBN calculates values of primary and secondary trophic indicators (yellow and pink 'indicator' nodes). Primary and secondary indicator values are used to produce ETI primary and secondary indicator scores, which are then combined to give the final ETI 'performance' score and band (red nodes).

Table 2-3: Bandings of indicators in ETI Tool 3. Primary and secondary indicators are banded A to D like NOF attributes used in the NPS-FM, but NOF bandings have not been set for estuaries at the time of preparing this report.

Indicator	A	B	C	D
Macroalgae	EQR ≥ 0.8	0.8 > EQR ≥ 0.6	0.6 > EQR ≥ 0.4	EQR < 0.4
Phytoplankton	Chl-*a* bands according to salinity as given in Table 2-2			
Sediment aRPD (cm)	aRPD ≥ 4	4 > aRPD ≥ 2.5	2.5 > aRPD ≥ 1.0	aRPD < 1
Oxygen concentration (mg L^{-1})	DO ≥ 7	7 > DO ≥ 6	6 > DO ≥ 5	DO < 5
Seagrass decline	Minor	Moderate	Severe	Extreme
TOC (%)	TOC < 0.5	0.5 ≤ DO < 1.2	1.2 ≤ DO < 2	TOC ≥ 2
Macrobenthos (NZ AMBI)	AMBI < 1.2	1.2 ≤ AMBI < 3.3	3.3 ≤ AMBI < 4.3	AMBI ≥ 4.3

2.5 Hydrodynamic modelling for large estuaries with sub-zones

The large estuaries and harbours (Kaipara, Manukau, Waitematā and Tāmaki) contain areas of interest to Auckland Council that may be considered sub-estuaries embedded within, or zones of, the larger systems. The tidal-prism dilution model used in ETI Tool 1 is not suitable for resolving these sub-estuaries, so instead we make use of existing numerical hydrodynamic models. These models provide the spatial resolution necessary to estimate nutrient concentrations within parts of the estuary and allow the impact of nutrient inputs from different sources to be compared within each zone. While specific details of each model are given below, a common approach was followed.

- The terminal reaches in the River Environment Classification (REC2.4) discharging to each estuary were identified and ranked by median discharge (largest to smallest). Median discharges were based on statistical models (Booker and Woods 2014), available via NZ River Maps (niwa.co.nz). Terminal reaches contributing to at least 90% of the total freshwater inflow were included for each model (it was not feasible to include all terminal reaches for some estuaries due to computational demands).

- For the selected terminal reaches, inflow was set to median flow values to represent 'typical' flow conditions. Unique tracers were assigned to each inflow, each with a source concentration of 1 (while units are not relevant for the calculations, this can be assumed to be 1 g m^{-3}).

- Each model was run for a 'spin-up' period sufficiently long that the initial conditions in the model domain were washed out. This period differed for each model domain but was determined to be sufficient when tracer concentrations had stabilised, and was up to 12 months in duration, depending on the model.

- Following the 'spin-up' period, the models were run for a further two weeks to capture a spring-neap cycle, and tracer concentrations recorded. Tracer concentrations were spatially averaged within defined areas of interest at each time-step, then averaged over time. Because each tracer was assigned a value of 1 at its source, the concentration of each tracer at any point in the model domain gives the portion of the water at that location originating from the source of that tracer.

- Nutrient (TN and TP) concentrations were estimated by multiplying the modelled tracer concentrations by the nutrient concentration in the inflow, then summing this for all tracers. This allowed the total nutrient concentration to be calculated, as well as the relative contribution of nutrients from each source to be identified.
- Nutrient concentrations in each freshwater source were estimated using predicted median concentrations (Whitehead, Fraser et al. 2022), available from NZ River Maps (niwa.co.nz).
- For ocean TN and TP concentrations, we used observed mean values from stations offshore or distant from the estuaries (Table 2-4). For the west coast estuaries (Kaipara, Manukau), the most offshore site is 43528 Manukau Harbour Offshore, located approximately 10 km north-west from the Manukau Harbour entrance (NZTM 1725884 E 5902805 N). On the east coast (Waitematā and Tāmaki), we chose 6315 Goat Island @ Waterfall Bay, the most northern site monitored by Auckland Council, and the most distant from significant river mouths so expected to best reflect oceanic conditions in this region.

Table 2-4: Ocean TN and TP concentrations used as boundary conditions in the tracer modelling for large estuaries. Oceanic concentrations were based on observed values from sites offshore sufficiently distant from the estuaries to reduce the influence of river plumes.

Estuary	Site used	TN (mg L^{-1})	TP (mg L^{-1})
Kaipara Harbour	43528 Manukau Hbr Offshore	0.109	0.010
Manukau Harbour	43528 Manukau Hbr Offshore	0.109	0.010
Tāmaki Estuary	6315 Goat Island @ Waterfall Bay	0.075	0.020
Waitematā Harbour	6315 Goat Island @ Waterfall Bay	0.075	0.020

By treating nutrients as passive (non-reactive) tracers, biogeochemical processes that may affect nutrient concentrations, such as denitrification, uptake, or release of nutrients by algae or bacteria, and sediment processes are not accounted for. The modelled concentrations are similar to the 'potential' concentrations used in the ETI but, being calculated using median concentrations and flows rather than the mean values used in ETI Tool 1, are not directly comparable to the nutrient band thresholds in Table 2-1.

2.5.1 Manukau Harbour

The model for the Manukau Harbour was developed in projects for Watercare Services Limited (Watercare) and Auckland Council (Reeve and Broekhuizen 2019; Broekhuizen and Reeve 2023), and uses the open-source 3D hydrodynamic model Delft-FM. This model uses an unstructured mesh with a combination of curvilinear rectangular grid cells in the main channels, estuary entrance, and nearby coastal area, and triangular grid cells over intertidal areas. This approach allows great flexibility in varying the resolution of the grid to obtain high resolution in areas of interest or high complexity, and lower resolution where such detail is not required, improving computational efficiency. The resolution of the grid varies from rectangles that are approximately 2,000 m offshore to triangles with sides less than 30 m in the upper reaches of Pahurehure Inlet. The grid contains 25,400 cells, and 10 layers in the vertical. The grid explicitly resolves the lower portions of the larger rivers, streams, and freshwater inflows.

The ocean boundaries of the model were forced with tides extracted from the NIWA EEZ tidal model (Walters, Goring et al. 2001). Inflows for the largest 72 streams and four wastewater treatment plant discharges (Māngere, Clarks, Kingseat, Waiuku) were included. Wastewater treatment plant discharges were based on data provided by Watercare. Meteorological data was obtained from the Auckland Airport automatic weather station for the period 2010–2011.

The model was run for the period 1 Jan 2010 to 31 Jan 2011, with data from the last 15 days used for calculating tracer concentrations.

Estuary zones were defined for (Figure 2-4):

- Māngere Inlet
- Pukaki/Waokauri Creek
- Puhinui Creek
- Pahurehure Inlet
- Clarks Creek
- Taihiki River
- Waiuku River
- The central Manukau (the main body of the estuary, excluding areas covered by other zones).

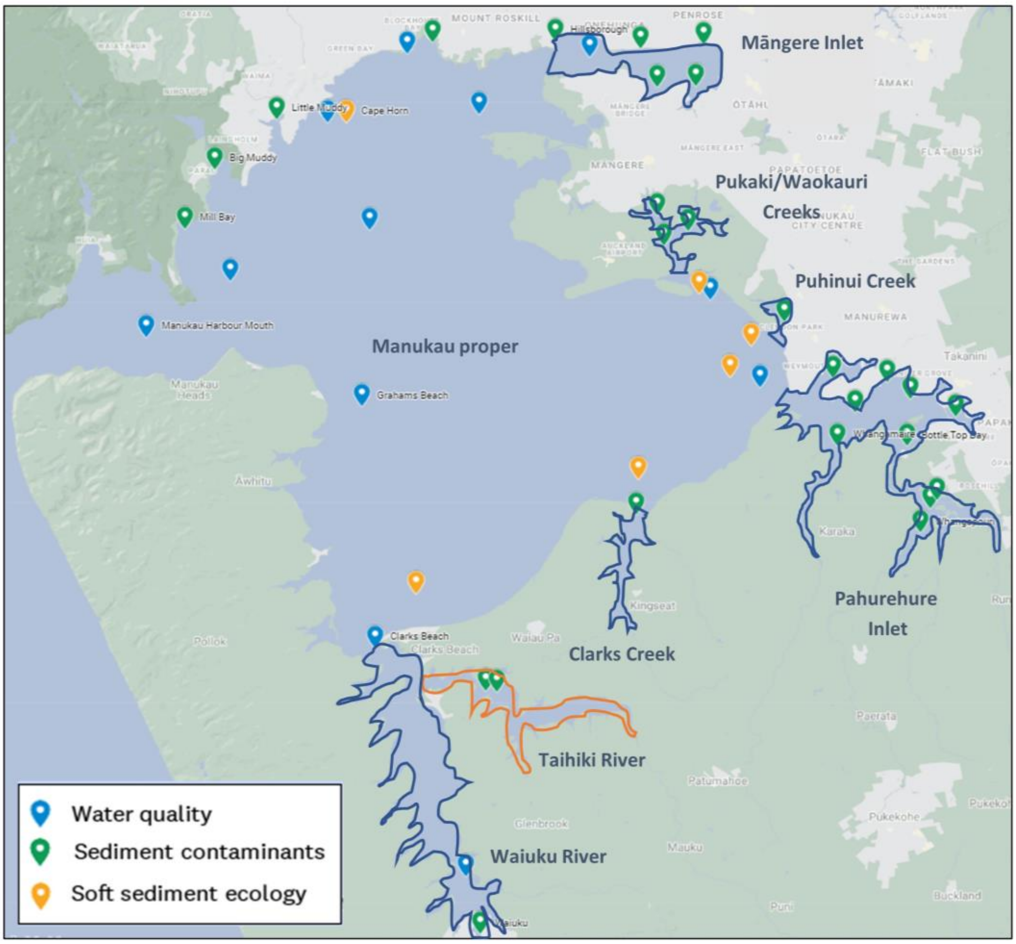

Figure 2-4: Zones within the Manukau Harbour. Potential nutrient concentrations, eutrophication susceptibility and areal sediment loading rates are calculated for the seven sub-estuaries or regions shown as well as the central harbour (Manukau proper). Taihiki River (in orange) joins to the Waiuku River zone but is considered separately. Also shown are locations of monitoring sites for water quality, sediment contaminants, and soft sediment ecology.

2.5.2 Kaipara Harbour

Kaipara Harbour was modelled using Delft3D, which is the predecessor to Delft3D-FM, differing in that it uses only curvilinear rectangular grid cells, not triangles, allowing less flexibility in varying the grid resolution throughout the model domain. This model used here was originally created to simulate sediment transport in the Kaipara Harbour (Pritchard, Stephens et al. 2012; Pritchard, Zammit et al. 2013; Reeve and Broekhuizen 2019).

The model grid has 63,074 grid cells, varying from 5 m resolution in the northern harbour to 1250 m offshore, and 5 layers in the vertical. The model was forced with tides on the open ocean boundary. Median flows from the 20 largest rivers were included, each with a unique tracer. Nine of these rivers are within the region administered by Auckland Council, with the other eleven rivers being within Northland Regional Council territory.

The model was run from 1 January to 31 July 2023 to reach quasi-steady state, then data from the two-week period 1 August 2023 – 15 August 2023 stored and used to calculate time-averaged tracer concentrations throughout the estuary and within each zone.

While the model grid covered the entire Kaipara Harbour, the regions of most interest to Auckland Council are in the southern part. Zones were defined that covered (Figure 2-5):

- Tauhoa Estuary
- Hoteo River
- Makarau Estuary
- Southern Compartment, from Shelley Beach south incorporating the Kaipara River and Kaukapakapa River
- Central Kaipara South zone, which the Kaipara Harbour south of a line between Okahukara Peninsula and South Head. This zone excludes the four zones listed above.

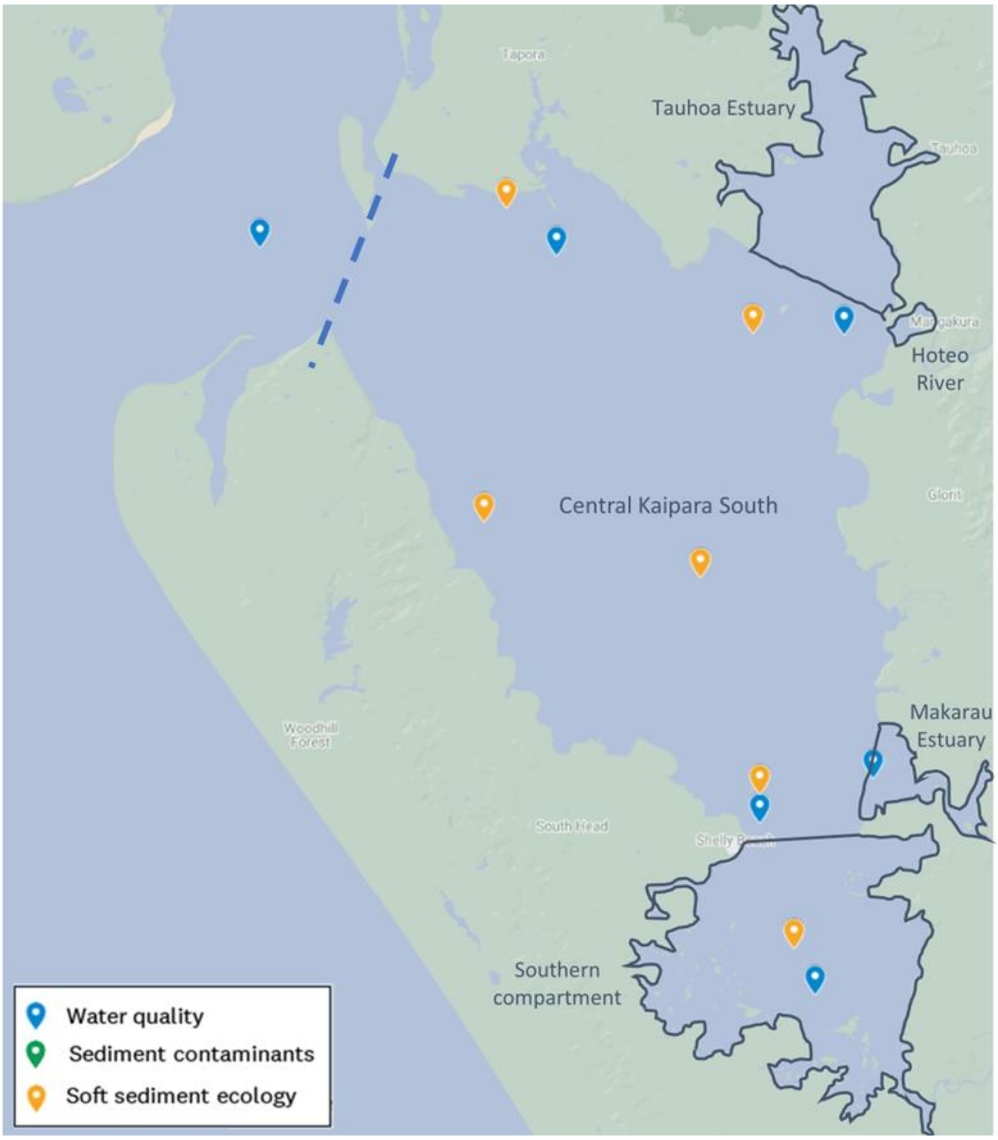

Figure 2-5: Zones within the estuaries in the southern Kaipara Harbour. Potential nutrient concentrations, eutrophication susceptibility and areal sediment loading rates are calculated for the four sub-estuaries or regions shown as well as the 'Central Kaipara South' section of the harbour. Also shown are locations of monitoring sites for water quality, sediment contaminants, and soft sediment ecology.

2.5.3 Waitematā Harbour and Tāmaki Estuary

The Waitematā Harbour and Tāmaki Estuary are modelled using Delft3D and are both included within the same model grid. This grid has a horizontal resolution of 78 × 78 m, contains 62,744 cells, and has 10 layers in the vertical. The model grid was developed for the 2021 America's Cup and is also used in the WETS (Wairoa Estuary, Tāmaki Strait) model developed under NIWA's Catchments to Estuaries research programme (Rautenbach, Xu et al., in review).

Freshwater inflows from 37 streams discharging to the Waitematā Harbour and 21 streams discharging to the Tāmaki Estuary were included in the model. Due to the high model resolution and the number of grid cells, the computational demand was too high to use unique tracers for all 58 inflows. Therefore, some inflows shared the same tracer. Small streams located near each other were assigned the same tracer. For example, in the Waitematā, Hendersons Creek, Momutu Stream, Rarawaru Stream, Lincoln Stream and Makomako Stream which are all located in the Hendersons

Creek arm of the estuary were assigned the same tracer. This reduced the number of tracers to 29 in the Waitematā Harbour and 10 in the Tāmaki Estuary.

The model was run twice – once using tracers in the Waitematā, and then again for tracers in the Tāmaki. The model was run from 1 Jan 2018 to 1 March 2018 for model spin up, and outputs for the period 2–16 March 2018 were stored for analysis.

In the Waitematā Harbour, zones were defined for (Figure 2-6):

- Brigham Creek
- Central Waitematā
- Hellyers Creek
- Hendersons Creek
- Hobson Bay
- Lucas Creek
- Paremoremo Creek
- Rangitopuni Creek
- Rarawaru Creek
- Upper Waitematā
- Waiarohai Inlet
- Whau Estuary.

In Tamaki Estuary, zones were defined for (Figure 2-7):

- Upper Tāmaki
- Lower Tāmaki.

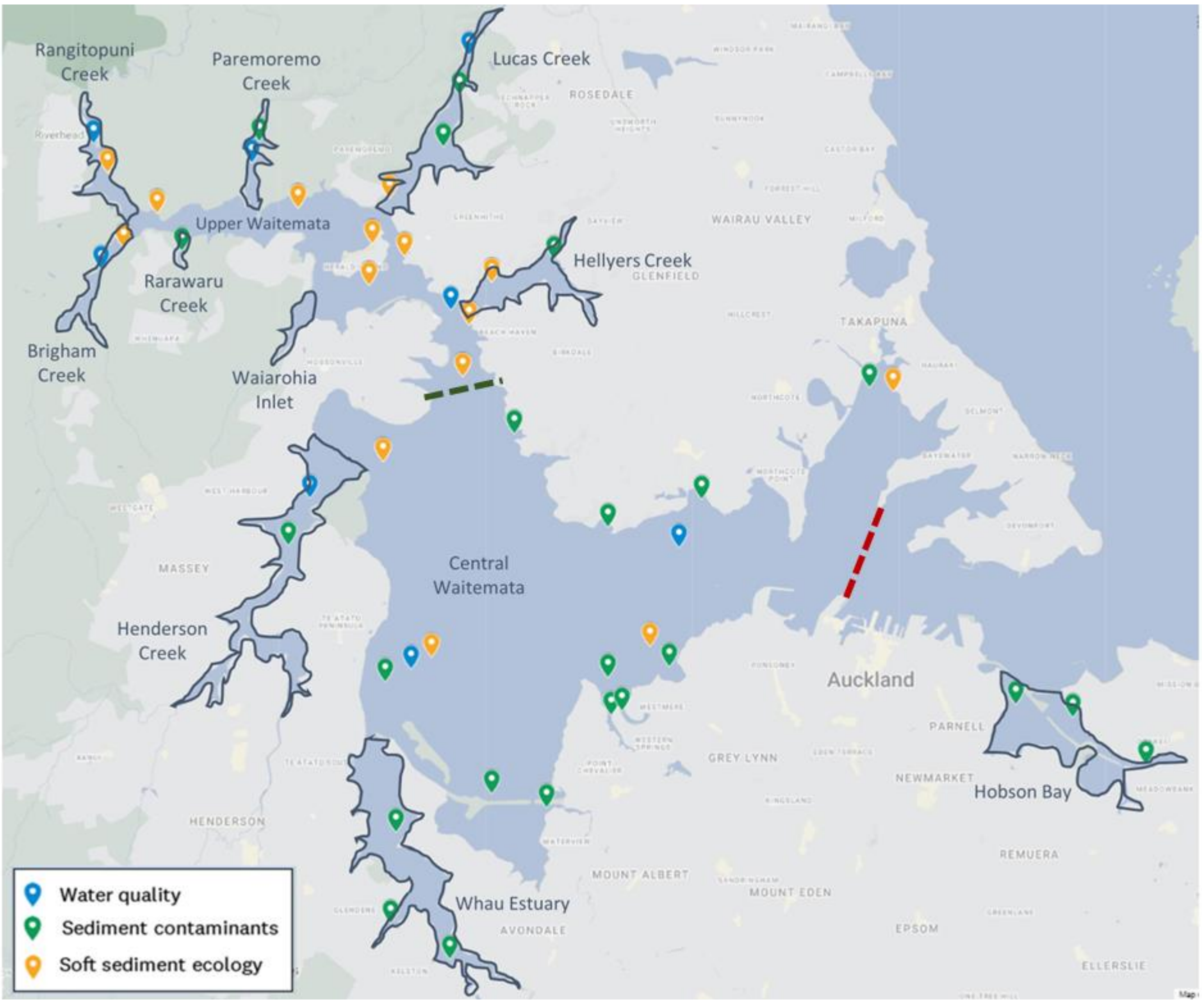

Figure 2-6: Zones within the Waitematā Harbour. Potential nutrient concentrations, eutrophication susceptibility and areal sediment loading rates are calculated for the twelve sub-estuaries or regions. The Upper Waitematā region is the inner harbour north of the dashed green line (excluding other subzones), and the Central Waitematā the area between the dashed red and green lines (excluding the Hendersons Creek and Whau Estuary regions). Also shown are locations of monitoring sites for water quality, sediment contaminants, and soft sediment ecology.

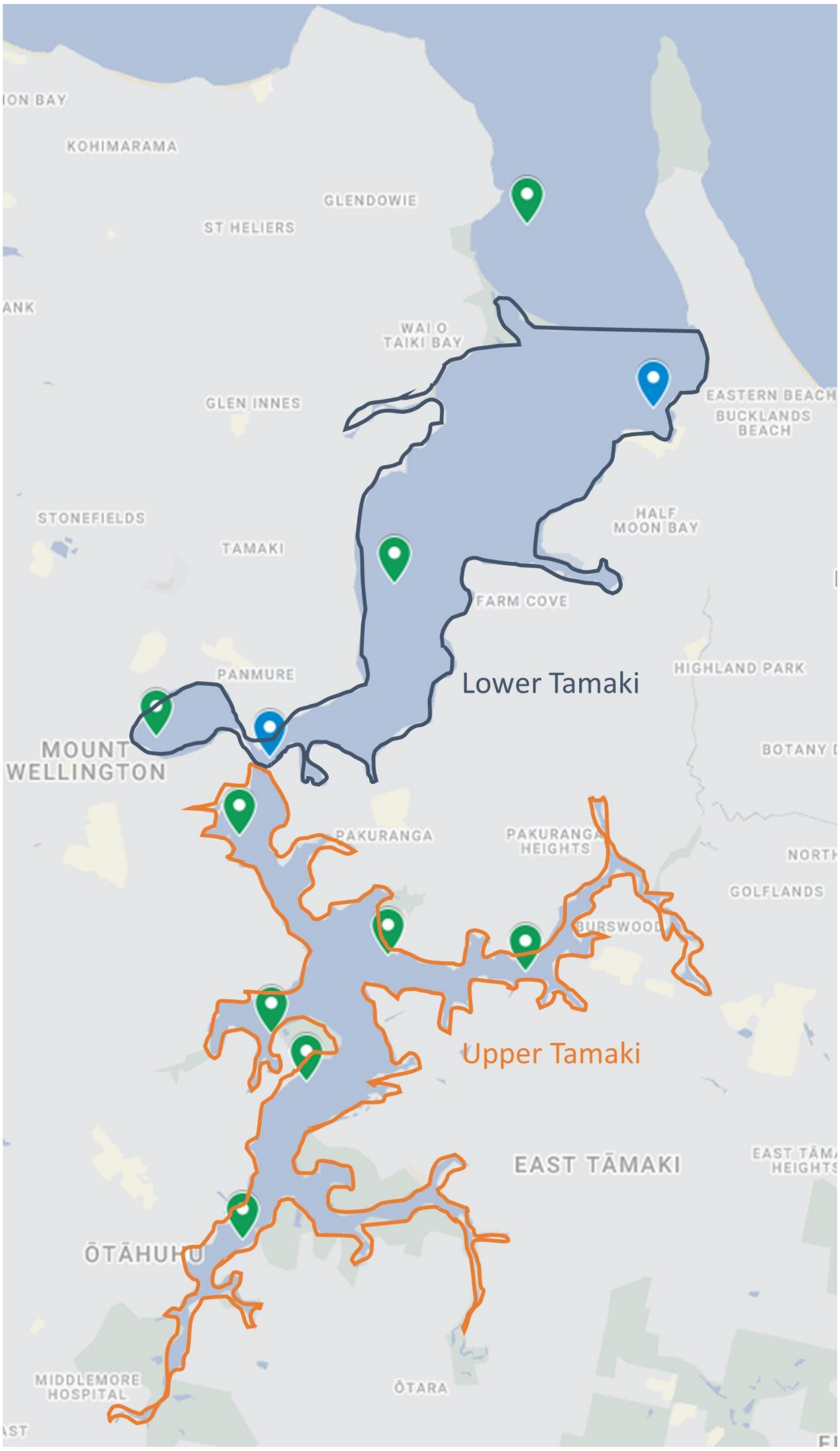

Figure 2-7: Zones within the Tāmaki Estuary. Potential nutrient concentrations, eutrophication susceptibility and areal sediment loading rates are calculated for the two regions shown as well as the whole estuary. Note that the Tāmaki Estuary is contained within the hydrodynamic model grid for the Waitematā.

3 Results

3.1 Sediment loading

Annual areal sediment loading rates for coastal hydrosystems in the Auckland region are compared to hydrosystems of the same type nationally in Figure 3-1. Table 3-1 gives the areal sediment loading rates and percentile ranking (compared to the national dataset) within hydrosystem type for the Auckland systems. As described above, the sediment yield estimator predicts 'contemporary' sediment loads but not necessarily present–day loads. Estuaries that do not receive high contemporary sediment loads relative to other New Zealand estuaries may still receive sediment loads markedly higher than their historical (pre-human) rates (Goff, 1997). We note also that this assessment does not consider trapping efficiency of sediments by estuaries, thus is not an indicator of sedimentation but rather of loading.

Only three of the Auckland estuaries rank in the top quartile nationally for areal sediment loading rate for their hydrosystems type. Pakiri River is classified as a tidal lagoon – permanently open (type 7A, Hume, Gerbeaux et al. 2016), and would rank in the top 5% nationally for areal sediment loading rates for tidal lagoons. While this estuary does have a moderate amount of intertidal area (35%), it is narrow and elongated with many similarities to a tidal river estuary (type 6B tidal river – spit enclosed). If classified as a tidal river, the Pakiri River would rank in lowest 20% for sediment loading rates.

The Wairoa River is classified as a shallow drowned valley and has a sediment areal loading rate within the top 10% for this hydrosystem type.

Turanga Creek, located within the Whitford Embayment System (WES), is also classified as a shallow drowned valley and ranks in the top 20% for areal sediment loading rate. It is among the smallest of New Zealand's 50 shallow drowned valleys (7th smallest by volume).

Other Auckland hydrosystems with elevated sediment loading rates (i.e., in the 2nd highest quartile by type) include the tidal lagoons Puhoi, Waiwera, and Te Muri-O-Tarariki; shallow drowned valleys Mangemangeroa Estuary and Matakana River; and coastal embayments Omaha Cove, Millon Bay and Awaawaroa Bay.

Note that the Sediment Load Estimator (Hicks, Semadeni-Davies et al. 2019) does not cover Great Barrier Island, so sediment loading rates are not available for the following systems:

- Tryphena Harbour
- Blind Bay
- Whangaparapara Harbour
- Port Fitzroy/Port Abercrombie
- Katherine Bay
- Rangiwhakaea Bay
- Whangapoua Creek
- Awana Bay

- Kaitoke Creek.

Table 3-1: Sediment loading rates and national percentile ranking by type for coastal hydrosystems in the Auckland region. Annual sediment loading rates were obtained from the Sediment Load Estimator (Hicks, Semadeni-Davies et al. 2019). Systems with loading rates ranking in the top quartile for their coastal system type (within New Zealand) are in bold text.

Coastal hydrosystems type	Estuary name	Sediment loading rate ($g/m^2/d$)	Percentile ranking
Beach stream	Waitakere River (Bethells Beach)	152	48%
Tidal river	Weiti River	2.04	0%
Tidal lagoon	**Pakiri River**	**173**	**95%**
	Puhoi River	20.7	67%
	Waiwera River	18.3	64%
	Te Muri-O-Tarariki	13.2	57%
	Orewa River	3.48	29%
	Okura River	2.61	26%
	Whangateau Harbour	1.55	14%
Shallow drowned valley	**Wairoa River**	**15.0**	**92%**
	Turanga Creek WES	**7.38**	**80%**
	Mangemangeroa Estuary WES	4.87	71%
	Matakana River	4.22	59%
	Pahurehure Inlet MHS	2.56	47%
	Kaipara Harbour System	1.84	39%
	Waikopua Creek WES	1.40	35%
	Puhinui Creek MHS	1.37	33%
	Lucas Creek WHS	1.31	31%
	Mahurangi Harbour System	1.31	29%
	Waitematā Harbour System	0.312	12%
	Manukau Harbour System	0.181	4%
	Tāmaki River	0.140	2%
Coastal embayment	Omaha Cove	1.53	63%
	Millon Bay	1.53	62%

Coastal hydrosystems type	Estuary name	Sediment loading rate ($g/m^2/d$)	Percentile ranking
	Awaawaroa Bay	1.33	58%
	Te Matuku Bay	1.08	49%
	South Cove Harbour	0.933	45%
	Matiatia Bay	0.625	36%
	Gardiner Gap	0.602	35%
	Hobbs Bay (Gulf Harbour)	0.595	33%
	Rocky Bay	0.501	32%
	Putiki Bay	0.456	28%
	Bon Accord Harbour	0.433	27%
	Mawhitipana Bay	0.432	26%
	Owhanake Bay	0.370	23%
	North Cove	0.267	17%
	Okoromai Bay	0.250	13%
	Huruhi Bay	0.0211	4%
	Islington Bay	0.0184	3%
	Oneroa Bay	0.0173	1%

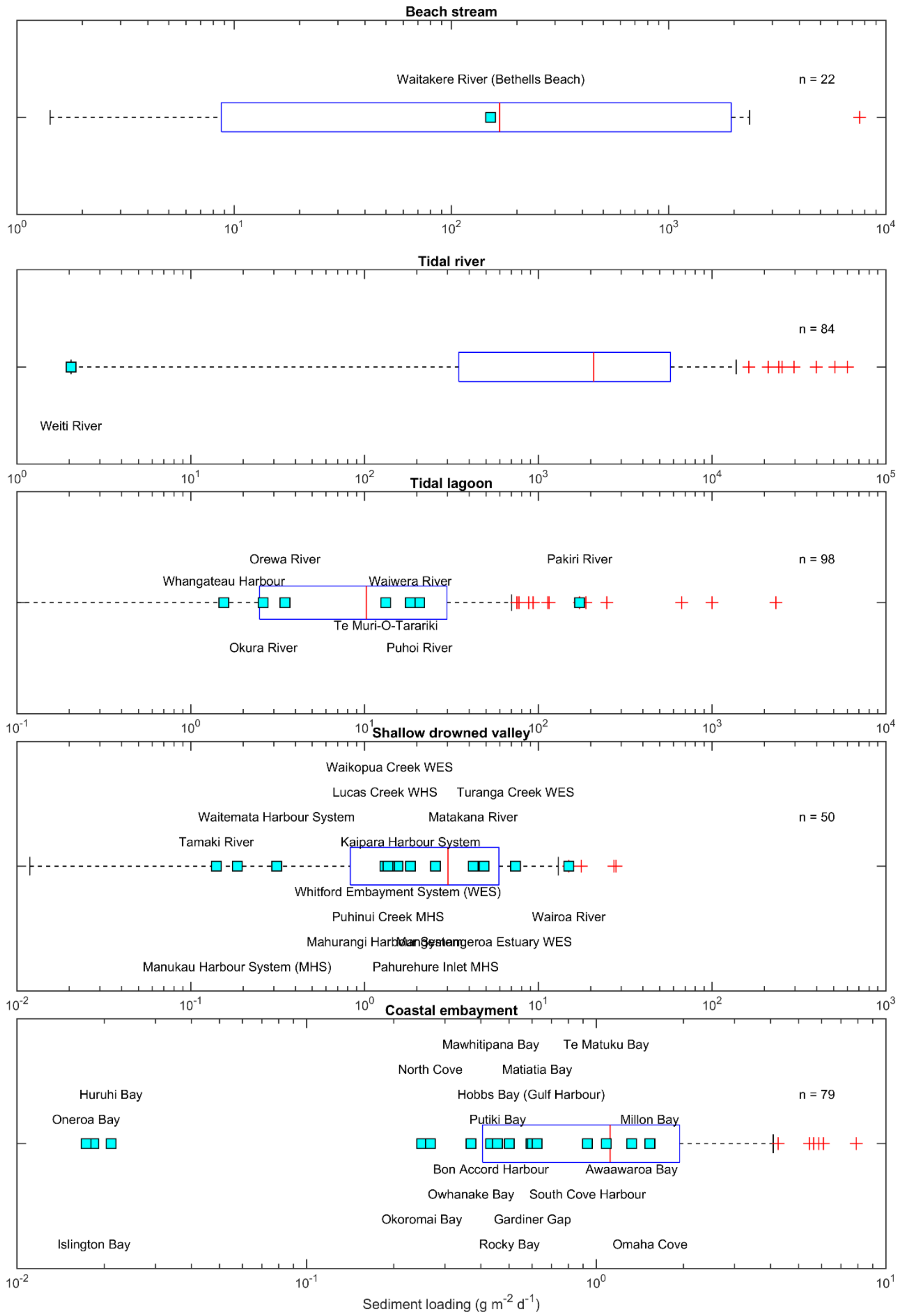

Figure 3-1: Comparison of mean areal sediment loading rates in Auckland estuaries to other New Zealand estuaries of similar type. Estuaries are classified according to the New Zealand Coastal Hydrosystems typology. Estuaries in the Auckland region are plotted as light blue squares. The box and whisker plots show the interquartile range for all New Zealand estuaries of that type, the bars extend to extremes of data not considered outliers, and red + indicate statistical outliers. The red bars inside boxes give medians.

While the Manukau Harbour overall has a low areal sediment loading, ranking in the 4th percentile for deep drowned valleys (Table 3-1), loading rates are higher in some of the estuary zones, particularly Pahurehure Inlet and Puhinui Inlet where the predicted loading exceeds 1 g m^{-2} d^{-1} (Table

3-2). We caution that these loading rates only consider the fine sediments supplied from streams that discharge directly into each estuary zone. Like nutrients, sediment can be advected into estuary zones from more distant streams, thus increasing the actual sediment load to each zone. However, more so than nutrients, sediments will settle out and be deposited on the estuary bed, depending on the settling velocity of the sediments, and factors that inhibit settlement or cause resuspension, including turbulence, currents, and wave action. Consequently, we cannot predict how much of the sediment delivered to each zone settles within that zone, nor how much may arrive from more distant sources.

The New Zealand sediment load estimator predicts that 24,700 t y^{-1} of sediment are delivered to Manukau Harbour from stream inflows. The five largest sediment sources are all in the Pahurehure Inlet (Hingaia Stream, Symonds Stream, Papakura Stream, Ngakoroa Stream and Whangapouri Creek), which collectively provide ~52% of the total sediment load to the Manukau Harbour. While Puhinui Inlet has a high areal sediment loading rate, this zone has a small area. Most of the sediment in this zone comes from a single inflow (Puhinui Creek).

Table 3-2: Sediment loading to zones within Manukau Harbour. Annual sediment loads into each zone are from (Hicks, Semadeni-Davies et al. 2019). Note that the sediment loading rates only consider the inputs from terminal reaches within each zone, and do not account for sediment coming from terminal reaches outside the zone. The sediment loading rate does not equate to deposition as it does not account for how much of the sediment is transported beyond the zone.

Subzone	Load (t y^{-1})	Area (m^2)	Sediment loading (g m^{-2} d^{-1})
Clarks Creek	520	2,465,000	0.578
Māngere Inlet	2.4	9,286,000	0.001
Pahurehure Inlet	14,236	15,392,000	2.534
Puhinui	323	642,000	1.379
Pukaki	31.0	2,323,000	0.037
Taihiki	1,048	6,442,000	0.446
Waiuku	3,237	17,904,000	0.495
Manukau (whole harbour)	24,700	374,189,000	0.181

Most of the sediment load to the Kaipara Harbour (325,600 t y^{-1}, or ~66% of the total sediment load) comes from the Wairoa River, in the north of the harbour. The southern part of the harbour (the Southern Compartment and the Central Kaipara South zones) have comparatively lower areal loading rates (1.333 g m^{-2} d^{-1} and 1.296 g m^{-2} d^{-1}, respectively) compared to the whole harbour (Table 3-3). Note that we have included all sediment inputs in the southern arm of the Kaipara when calculating the areal loading rate to the Central Kaipara South zone, although the surface area used excludes the other subzones. The Hoteo River has a very high sediment load rate (140 g m^{-2} d^{-1}), which is due to both a high sediment load (44,352 t y^{-1}, the second largest sediment source to the Kaipara Harbour) and because this zone is small (867,100 m^2). It is likely that a high portion of the sediment load from the Hoteo River is exported outside of this zone. The Makarau Estuary also has a high areal sediment loading rate compared to the rest of the estuary (9.7 g m^{-2} d^{-1}). This loading rate would lie around the 50th percentile for New Zealand tidal lagoon estuaries. The Kaipara River (11,030 t y^{-1}) and Kaukapakapa River (10,719 t y^{-1}) are the third and fourth largest sources of sediment to the Kaipara Harbour. These rivers merge as the enter the southern part of the harbour, collectively supplying most of the sediment in this region. While the areal sediment loading rate to the Southern Compartment may not appear particularly high (1.333 g m^{-2} d^{-1}), this subzone as defined has a large area, and the loading rate would be higher if the subzone was restricted to closer to the Kaipara River mouth.

Table 3-3: Sediment loading to zones within Kaipara Harbour. Note that the sediment load to the Central Kaipara South subzone includes all sediments in the southern harbour. Refer to the caption for Table 3-2 for further details.

Subzone	Load (t y^{-1})	Area (m^2)	Sediment loading (g m^{-2} d^{-1})
Tauhoa Estuary	9,328	25,603,000	0.998
Hoteo River	44,352	867,100	140.1
Makarau Estuary	16,693	4,712,000	9.706
Southern Compartment	24,748	50,875,000	1.333
Central Kaipara South	113,504	240,411,900	1.293
Kaipara (whole harbour)	498,474	743,061,000	1.844

The Waitematā Harbour has a lower overall areal sediment loading rate than most shallow drowned valleys (the estuary type according to the NZCHS), but much of the load comes from the Rangitopuni Creek and Henderson Creek zones of the estuary (Table 3-4). The Rangitopuni Creek zone has the highest areal loading rate (23.6 g m^{-2} d^{-1}) of the Waitematā estuary zones, followed by Paremoremo Creek (4.8 g m^{-2} d^{-1}).

The sediment load indicator assumes that urban land cover has no sediment discharge (Hicks, Semadeni-Davies et al. 2019), and consequently zero sediment loads are predicted for many of the sub-catchments of the Waitematā Harbour. While urban land covers do generate sediment loads, the physical characteristics of urban sediments and their sources are different from those in rural areas and are highly variable. The main sources of urban sediments are soils, organic material (e.g., leaf fragments), litter and particles from road and tyre wear and tear, and the importance of these sources will vary with land use (e.g., residential, commercial, or industrial land). Sediment yields from urban soils are generally lower than rural soils due to compaction, the exception being earthworks during urban development, however consenting usually requires that sediment traps are in place before top-soil is removed. Sediment loads from impervious surfaces other than roads, such as roof and pavements, tend to be low. Urban stormwater treatment devices, where present, are often designed to target sediment removal to reduce the level of particulate contaminants such as heavy metals, which have an affinity with sediments. We also note that there is insufficient sediment load data from predominantly urban streams in the calibration dataset with which to calibrate an urban land cover coefficient. Moreover, Land Resource Inventory based data, such as erosion terrains, do not have data for urban areas. For these reasons, sediment loads from urban areas are not calculated by the sediment load estimator.

Table 3-4: Sediment loading to zones within Waitematā Harbour. Refer to the caption for Table 3-2 for further details.

Subzone	Load ($t\ y^{-1}$)	Area (m^2)	Sediment loading ($g\ m^{-2}\ d^{-1}$)
Rangitopuni Creek	5126.9	596,000	23.62
Henderson Creek	2049.2	2,048,000	2.742
Brigham Creek	263.1	505,000	1.429
Lucas Creek	724.7	1,460,000	1.360
Whau Estuary	0	3,395,000	0
Paremoremo Creek	757.6	437,000	4.748
Hobson Bay	0	2,490,000	0
Hellyers Creek	68.3	1,252,000	0.150
Waiarohia Inlet	41.8	299,000	0.382
Rawawaru	10.3	56,600	0.498
Waitematā Harbour	9082.2	80,282,000	0.310

The sediment load estimator predicts that all the sediment enters the Tāmaki Estuary in the upper part of the estuary (Table 3-5), and mostly (96% of the load) from Otara Creek. As noted for the Waitematā, the sediment load estimator does not predict sediment loads from urban land cover, thus sediment inputs may be underestimated, particularly for the lower estuary.

Table 3-5: Sediment loading to the Tāmaki Estuary. Refer to the caption for Table 3 2 for further details.

Subzone	Load ($t\ y^{-1}$)	Area (m^2)	Sediment loading ($g\ m^{-2}\ d^{-1}$)
Upper Tāmaki	863.3	5,044,000	0.472
Tāmaki Estuary	863.3	16,794,000	0.142

3.2 Nutrient load comparisons

Annual nutrient loads to each estuary predicted by CLUES, NZRiverMaps and the Freshwater Management tool are compared in Figure 3-2. As noted above, annual loads from NZRiverMaps were estimated by multiplying median nutrient concentrations by mean flow, which is likely to bias the estimated loads downwards because nutrient concentrations are typically higher during high flow events. The annual loads from CLUES and NZRiverMaps loads are strongly correlated for both TN and TP ($R^2 > 0.8$), but TN loads from NZRiverMaps are about half those from CLUES, and TP loads about one quarter. The correlation between CLUES and the FWMT are weaker ($R^2 < 0.5$). The FWMT TN loads are around 11% of those from CLUES, while TP loads are 23% of those predicted by CLUES, similar to the NZRiverMaps values. Examination of the FWMT coastal 'nodes' (catchments) and 'pour points' (terminal reaches) during the project suggested that further work would be required to use FWMT nutrient concentration and flow data for estuary limit setting. Specifically, FWMT nodes on the coastal boundary do not appear to cover the full upstream catchment of the pour points. In addition, the FWMT coastal pour points do not cover many of the known rivers and streams entering estuaries in the Auckland region. Further information on the structure and purpose of the FWMT can be found in the reports documenting the tool at:

https://www.knowledgeauckland.org.nz/publications/freshwater-management-tool-report-1-baseline-data-inputs/

For the purposes of this report, we have used the CLUES nutrient loads and flows in our calculations in ETI Tool 1 and Tool 3 calculations but have used NZRiverMaps median concentrations and median flows for the spatially resolved modelling of Manukau, Kaipara, Waitematā Harbours and Tāmaki Estuary.

A comparison of CLUES, NZRiverMaps and 'measured' loads at upstream SoE monitoring sites is shown in Table 3-6. These comparisons suggest that:

1. The period of data record may affect the estimates of nutrient load. Measured loads at or near terminal reaches through time would aid understanding of year-to-year variation in loads to estuaries not captured by steady-state models (like CLUES and NZRiverMaps) or models calibrated on limited data records.

2. As at terminal reaches, CLUES loads are well-correlated with, but higher than NZRiverMaps loads for both TN and TP.

Table 3-6: Comparison of modelled (CLUES and NZRiverMaps models) and measured nutrient loads (in tonnes per year) at monitoring sites upstream of estuaries. Measured loads are provided using the approximate data range across which data were sourced to calibrate the FWMT tool (2013–2017) and also using the full available dataset. LAWA (Land, Air, Water Aotearoa) site IDs are given as identifiers.

LAWA_site_id	Site Name	Measured TN (2013-2017)	Measured TP (2013-2017)	Measured TN (full record)	Measured TP (full record)	CLUES TN	CLUES TP	NZRM TN	NZRM TP
ARC-00004	Lucas Creek at Gills Rd Bridge	2.844	0.201	3.163	0.290	3.854	0.440	1.785	0.153
ARC-00013	Opanuku Stream	3.060	0.306	3.976	0.485	5.328	0.654	2.290	0.211
ARC-00027	West Hoe Stream	0.012	0.003	0.035	0.006	0.964	0.358	0.123	0.021
ARC-00074	Oteha River @ Days Bridge	4.849	0.391	7.015	0.546	7.254	0.810	4.749	0.387
ARC-00035	Kaukapakapa @ Taylors Rd	19.977	2.138	31.417	3.142	54.604	6.231	30.301	2.252

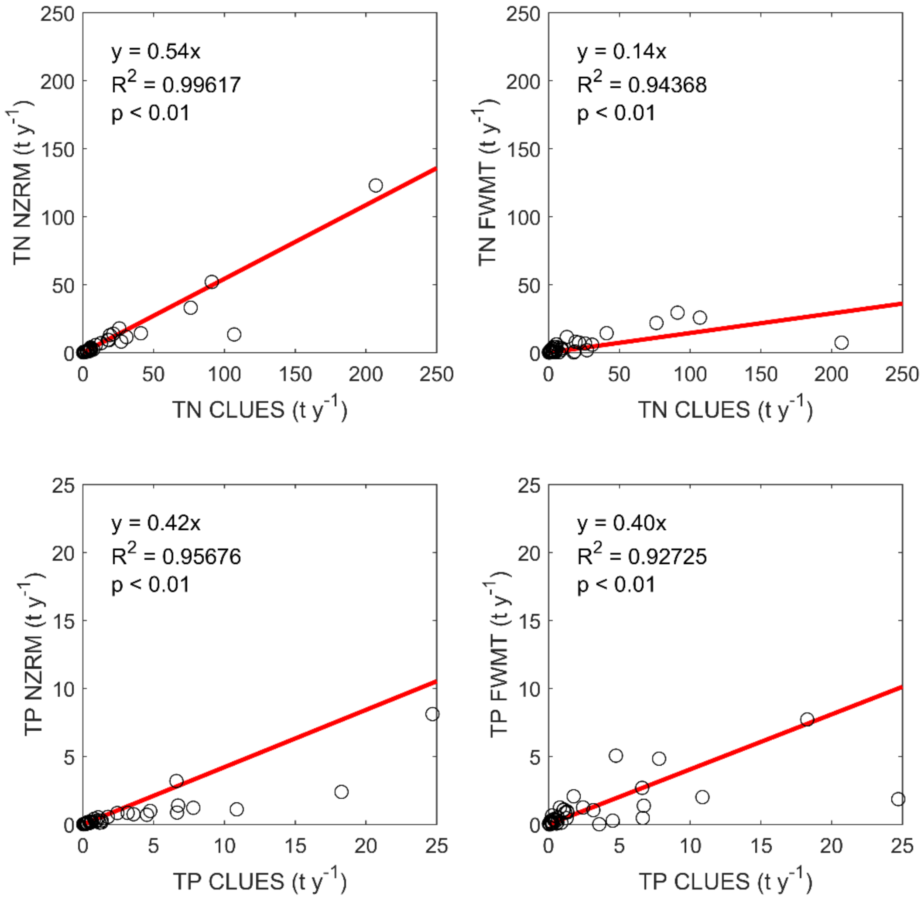

Figure 3-2: Comparison of predicted annual nutrient loads to estuaries. The plots show modelled annual nutrient loads from CLUES, NZ River Maps (NZRM) and the Freshwater Management Tool (FWMT). Circles show data for each of the modelled estuaries, and the red lines the best fit linear regressions with zero intercept.

3.3 ETI Tool 1 results

Results of the ETI Tool 1 susceptibility screening are given in Table 3-7. Only one of Auckland's estuaries scored as having a high (C-band) susceptibility to eutrophication. The Wairoa River scores in the C-band based on the relatively high potential TN concentration, along with significant intertidal area (~42%) which may support macroalgal blooms. This estuary is also predicted to have the highest peak chl-*a* concentration (~18 µg L^{-1}), ranking in a D-band for phytoplankton susceptibility. Here, the overall susceptibility has been assigned based on the susceptibility to macroalgal blooms, as the secondary effects of these are often (but not always) more severe than of phytoplankton blooms.

Other estuaries where the TN concentrations are within the B-band for macroalgae but approach the C-band threshold are Pakiri River and Waitakere River (Bethells Beach), although the low salinity in Waitakere River may inhibit growth of estuarine macroalgae (Dudley, Barr et al. 2022).

Regarding phytoplankton, estuaries that score in the C-band are Whangateau Harbour and Waiwera River. These are both tidal lagoons, which are commonly shallow and have strong vertical mixing. These characteristics help mitigate the effects of high phytoplankton concentrations such as light attenuation and low oxygen concentrations, therefore their overall susceptibility has been based on macroalgal susceptibility (B-band in both cases). Eleven estuaries have flushing times too short to support phytoplankton growth (although phytoplankton blooms are possible if mouth closures occur). In all estuaries except Whangateau Harbour, nitrogen is likely to be the limiting nutrient for phytoplankton growth. Phosphorus may be the limiting nutrient for phytoplankton growth in Whangateau Harbour.

The large estuaries Waitematā, Tāmaki, and Manukau have also been assessed using ETI Tool 1 for comparison to results from the hydrodynamic modelling. All three rank as having low susceptibility to macroalgal blooms (A-band), Waitematā and Manukau rank as having moderate susceptibility to phytoplankton (B-band) while Tāmaki has low susceptibility to phytoplankton (A-band).

Table 3-7: ETI Tool 1 susceptibility results for Auckland estuaries. Annual TN and TP loads are derived from the NIWA CLUES model. Salinity and potential Total Nitrogen (TN) concentrations in the estuary are predicted using simple modified tidal prism models. Peak phytoplankton accumulation potential as chlorophyll-*a* (chl-*a*) is predicted using a growth model and indicates the maximum likely chl-*a* accumulation providing only nitrogen and phosphorus availability are considered. Limiting condition for phytoplankton indicates whether nitrogen, phosphorus or flushing time is likely to be limiting the maximum phytoplankton accumulation (flushing time indicates that the flushing time is too short to support phytoplankton accumulation under usual flow conditions with the mouth open).

ID	Estuary name	NZCHS code	NZCHS class	Intertidal area (%)	Salinity	Summer flushing time (d)	Potential TN (mg m^{-3})	Chl-*a* accum. (µg l^{-1})	Limiting factor for phytoplankton	Macroalgal band	Phytoplankton band	Overall band
49	Pakiri River	7A	Tidal lagoon (permanently open)	35.24	21.2	2.4	327	0.0	flushing time	B	A	**B**
50	Omaha Cove	11	Coastal embayment	0	33.5	18.4	64	3.9	N	A	B	**B**
51	Whangateau Harbour	7A	Tidal lagoon (permanently open)	85.44	34.0	6.2	186	9.3	P	B	C	**B**
52	Millon Bay	11	Coastal embayment	61.55	34.2	5.8	65	0.01	N	A	A	**A**
53	Matakana River	8	Shallow drowned valley	75.98	31.8	4.9	139	0.6	N	A	A	**A**
78	Mahurangi Harbour System	8	Shallow drowned valley	51.18	34.2	7.7	49	1.0	N	A	A	**A**
79	Te Muri-O-Tarariki	7A	Tidal lagoon (permanently open)	99.93	30.6	4.6	155	5.3	N	A	B	**A**
80	Puhoi River	7A	Tidal lagoon (permanently open)	70.58	29.6	6.5	163	5.5	N	A	B	**A**
81	Waiwera River	7A	Tidal lagoon (permanently open)	64.49	28.9	6.6	218	9.9	N	B	C	**B**
82	Orewa River	7A	Tidal lagoon (permanently open)	89	31.4	5.3	183	6.1	N	B	B	**B**
83	Okoromai Bay	11	Coastal embayment	27	34.9	6.3	37	0	flushing time	A	A	**A**
84	Hobbs Bay (Gulf Harbour)	11	Coastal embayment	0	33.3	9.0	44	1.7	N	A	A	**A**
85	Weiti River	6B	Tidal river mouth (spit enclosed)	63.04	33.1	5.0	93	0	flushing time	A	A	**A**
86	Okura River	7A	Tidal lagoon (permanently open)	79.27	30.3	4.8	156	1.4	N	A	A	**A**
90	Mangemangeroa Estuary WES	8	Shallow drowned valley	86.92	29.6	4.8	98	0	flushing time	A	A	**A**
91	Turanga Creek WES	8	Shallow drowned valley	73.64	32.8	4.9	183	7.1	N	B	B	**B**
92	Waikopua Creek WES	8	Shallow drowned valley	99.97	33.9	5.1	115	1.3	N	A	A	**A**
93	Wairoa River	8	Shallow drowned valley	41.96	26.2	6.7	354	18.3	N	C	D	**C**
220	Waitakere River (Bethells Beach)	4C	Beach Stream (stream with pond)	88.69	7.5	0.4	311	0	flushing time	B	A	**B**

ID	Estuary name	NZCHS code	NZCHS class	Intertidal area (%)	Salinity	Summer flushing time (d)	Potential TN (mg m^{-3})	Chl-*a* accum. (µg l^{-1})	Limiting factor for phytoplankton	Macroalgal band	Phytoplankton band	Overall band
250	North Cove	11	Coastal embayment	37.32	34.8	7.4	36	0.4	N	A	A	**A**
251	Bon Accord Harbour	11	Coastal embayment	19.16	34.7	11.8	37	2.3	N	A	A	**A**
252	South Cove Harbour	11	Coastal embayment	30.59	34.6	6.2	43	0	flushing time	A	A	**A**
253	Gardiner Gap	11	Coastal embayment	59.61	34.6	5.1	46	0	flushing time	A	A	**A**
254	Islington Bay	11	Coastal embayment	6.94	35.0	8.5	31	0.9	N	A	A	**A**
255	Matiatia Bay	11	Coastal embayment	2.86	34.9	9.1	34	1.3	N	A	A	**A**
256	Owhanake Bay	11	Coastal embayment	2.3	35.0	9.8	33	1.6	N	A	A	**A**
257	Oneroa Bay	11	Coastal embayment	0.66	35.1	16.5	31	2.5	N	A	A	**A**
258	Mawhitipana Bay	11	Coastal embayment	8.76	34.9	13.0	41	2.5	N	A	A	**A**
259	Te Matuku Bay	11	Coastal embayment	75.88	34.3	5.1	45	0	flushing time	A	A	**A**
260	Awaawaroa Bay	11	Coastal embayment	28.73	34.7	7.5	41	0.7	N	A	A	**A**
261	Rocky Bay	11	Coastal embayment	30.43	34.8	7.0	38	0.3	N	A	A	**A**
262	Putiki Bay	11	Coastal embayment	35.45	34.9	6.6	40	0.1	N	A	A	**A**
263	Huruhi Bay	11	Coastal embayment	11.68	35.1	11.3	32	1.8	N	A	A	**A**
264	Tryphena Harbour	11	Coastal embayment	4.12	34.9	34.8	36	3.6	N	A	B	**B**
265	Blind Bay	11	Coastal embayment	5.27	34.7	29.5	40	3.6	N	A	B	**B**
266	Whangaparapara Harbour	11	Coastal embayment	13.79	34.5	32.2	39	3.8	N	A	B	**B**
267	Port Fitzroy/Port Albercrombie	9	Deep drowned valley	3.23	35.0	47.4	36	3.6	N	A	B	**B**
268	Katherine Bay	11	Coastal embayment	3.33	34.4	20.8	42	3.5	N	A	B	**B**
269	Rangiwhakaea Bay	11	Coastal embayment	1.61	33.8	21.8	46	3.9	N	A	B	**B**
270	Whangapoua Creek	7A	Tidal lagoon (permanently open)	93.97	32.6	5.2	57	0	flushing time	A	A	**A**
271	Awana Bay	4C	Beach Stream (stream with pond)	45	22.8	3.3	178	0	flushing time	B	A	**A**
272	Kaitoke Creek	4C	Beach Stream (stream with pond)	30.51	22.8	2.7	160	0	flushing time	A	A	**A**
87	Waitematā Harbour System	8	Shallow drowned valley	36.16	34.5	9.9	57	3.0	N	A	B	**B**

ID	Estuary name	NZCHS code	NZCHS class	Intertidal area (%)	Salinity	Summer flushing time (d)	Potential TN (mg m-3)	Chl-*a* accum. (µg l-1)	Limiting factor for phytoplankton	Macroalgal band	Phytoplankton band	Overall band
88	Tāmaki River	8	Shallow drowned valley	40	34.6	6.7	63	2.5	N	A	A	**A**
219	Manukau Harbour System (MHS)	8	Shallow drowned valley	61.8	34.6	16.1	60	4.2	N	A	B	**A**

3.4 ETI Tool 3 results

The overall ETI Tool 3 results are given in Table 3-8, while the probability distributions for bandings of each primary and secondary indicator are given in Appendix B. The BBN predicts that most estuaries will score in the A-band under current nitrogen and sediment loads. Estuaries that score in the B-band are Omaha Cove, Wairoa River, Awana Bay, and Waitematā. Omaha Cove is ranked in B-band due to predicted elevated chlorophyll-*a* concentrations and potential for oxygen depletion. Wairoa River scores in B-band due to elevated macroalgal EQR and reduced aRPD. Awana Bay scores as having nearly equal probability of being in either band A or B with 25% probability of scoring in band C. This wide distribution results from the estuary flushing time being close to the minimum required for phytoplankton blooms to occur, such that the BBN predicts either no or moderate amounts of phytoplankton accumulation. Most secondary indicators are likely to remain in a healthy state. Waitematā scores in B-band due to the elevated chl-*a* concentrations. Having an intertidal area between 5 – 40%, the BBN uses the higher of the macroalgal and phytoplankton scores when calculating the primary indicator score. Generally, the ETI BBN bands are lower (indicating lower susceptibility to eutrophication) than the ETI Tool 1 susceptibility bands. Part of the reason for this is that for macroalgae, the BBN makes a prediction of the mean EQR (i.e., the dashed regression line in Figure 2-1) along with the probability distribution for that prediction, based on the predictor interval. ETI Tool 1 applies a 25% under protection risk so in effect predicts a lower (worse) EQR score for an equivalent potential TN concentration.

Table 3-8: ETI Tool 3 BBN results. The ETI Tool 3 BBN gives a predicted ETI score, along with the probability that the estuary scores in each ETI band. The band (A-D) with the highest probability is shaded.

ID	Estuary name	ETI score	std-dev ETI	Band probability			
				A	B	C	D
49	Pakiri River	0.207	0.082	70%	30%	0%	0%
50	Omaha Cove	0.327	0.099	24%	73%	3%	0%
51	Whangateau Harbour	0.203	0.096	71%	29%	1%	0%
52	Millon Bay	0.166	0.078	85%	15%	0%	0%
53	Matakana River	0.177	0.087	80%	20%	0%	0%
78	Mahurangi Harbour System	0.160	0.073	87%	13%	0%	0%
79	Te Muri-O-Tarariki	0.199	0.097	72%	28%	1%	0%
80	Puhoi River	0.200	0.096	72%	28%	0%	0%
81	Waiwera River	0.242	0.112	56%	42%	2%	0%
82	Orewa River	0.197	0.097	72%	27%	0%	0%
83	Okoromai Bay	0.220	0.084	63%	37%	0%	0%
84	Hobbs Bay (Gulf Harbour)	0.205	0.091	68%	32%	0%	0%
85	Weiti River	0.154	0.070	90%	10%	0%	0%
86	Okura River	0.197	0.097	72%	27%	0%	0%
90	Mangemangeroa Estuary WES	0.166	0.077	85%	15%	0%	0%
91	Turanga Creek WES	0.199	0.097	72%	28%	1%	0%
92	Waikopua Creek WES	0.180	0.086	80%	20%	0%	0%

ID	Estuary name	ETI score	std-dev ETI	Band probability			
				A	B	C	D
93	Wairoa River	0.327	0.137	31%	57%	11%	0%
220	Waitakere River (Bethells Beach)	0.203	0.090	72%	28%	0%	0%
250	North Cove	0.220	0.084	63%	37%	0%	0%
251	Bon Accord Harbour	0.220	0.084	63%	37%	0%	0%
252	South Cove Harbour	0.220	0.084	63%	37%	0%	0%
253	Gardiner Gap	0.160	0.073	87%	13%	0%	0%
254	Islington Bay	0.220	0.084	63%	37%	0%	0%
255	Matiatia Bay	0.205	0.091	68%	32%	0%	0%
256	Owhanake Bay	0.205	0.091	68%	32%	0%	0%
257	Oneroa Bay	0.206	0.091	68%	32%	0%	0%
258	Mawhitipana Bay	0.221	0.085	63%	37%	0%	0%
259	Te Matuku Bay	0.160	0.073	87%	13%	0%	0%
260	Awaawaroa Bay	0.220	0.084	63%	37%	0%	0%
261	Rocky Bay	0.220	0.084	63%	37%	0%	0%
262	Putiki Bay	0.220	0.084	63%	37%	0%	0%
263	Huruhi Bay	0.221	0.085	63%	37%	0%	0%
264	Tryphena Harbour	0.206	0.091	68%	32%	0%	0%
265	Blind Bay	0.221	0.085	63%	37%	0%	0%
266	Whangaparapara Harbour	0.221	0.084	63%	37%	0%	0%
267	Port Fitzroy/Port Albercrombie	0.206	0.091	68%	32%	0%	0%
268	Katherine Bay	0.206	0.091	68%	32%	0%	0%
269	Rangiwhakaea Bay	0.206	0.091	68%	32%	0%	0%
270	Whangapoua Creek	0.166	0.078	85%	15%	0%	0%
271	Awana Bay	0.348	0.177	36%	39%	25%	0%
272	Kaitoke Creek	0.188	0.074	78%	22%	0%	0%
87	Waitematā Harbour System	0.320	0.102	27%	70%	3%	0%
88	Tāmaki River	0.169	0.079	84%	16%	0%	0%
219	Manukau Harbour System	0.169	0.079	84%	16%	0%	0%

3.5 Indicative nutrient load thresholds

Indicative load thresholds are estimated by determining the catchment loads corresponding to changes in ETI Tool 1 eutrophication susceptibility bands (Table 3-9). TN thresholds can be estimated for macroalgae, and both TN and TP thresholds for phytoplankton. Thresholds for macroalgae and phytoplankton susceptibility differ, and in most cases the TN band thresholds are lower for phytoplankton. In some estuaries, the flushing time is predicted to be too short to sustain phytoplankton growth, in which case no load band thresholds for phytoplankton are reported. There are some estuaries where the ETI Tool 1 susceptibility screening (Table 3-7) indicates the flushing time is too short to support phytoplankton, yet phytoplankton susceptibility load bands have been calculated (Okoromai Bay, Weiti River, Mangemangeroa Estuary, South Cove Harbour, Gardiner Gap, Te Matuku Bay, and Whangapoua Creek). This occurs because under present nutrient loads, nutrient concentrations in these estuaries are predicted to be so low that phytoplankton growth rates are strongly nutrient limited, and a longer flushing time is required so that phytoplankton can accumulate faster than they are flushed from the estuary (see Figure 2-2). However, the estuary flushing time is long enough that if nutrient loads increase, phytoplankton growth rates will increase, and phytoplankton can accumulate.

The most appropriate load thresholds (based on macroalgae or phytoplankton) should be selected based on estuary type and properties. Using the same criteria as in the ETI Tool 1 screening, the most appropriate load thresholds are identified in bold text in Table 3-9. Current annual TN and TP loads predicted by CLUES are included in Table 3-9 for comparison.

Note that these load band thresholds are based on ETI Tool 1 which predicts susceptibility to eutrophication, but the predicted susceptibility may not agree with the actual health of the estuary if there are other factors controlling eutrophication, or if the modelled catchment loads or estuary dilution are inaccurate. Therefore, we strongly recommend that the load thresholds be used only to help prioritise which estuaries warrant further investigation, rather than to set management targets, and to compare predicted susceptibility with actual estuary condition to assess whether the load bands are appropriate.

Table 3-9: Estimated TN and TP loads corresponding to changes in ETI susceptibility bands for macroalgae and phytoplankton. While loads are given for both macroalgae and phytoplankton susceptibility bands, the most appropriate load bands considering estuary type (NZCHS class) are in bold. Note that for some estuaries, phytoplankton susceptibility load band thresholds are not given because the flushing time is predicted to be too short to sustain phytoplankton growth – these cells are left blank in the table. In other estuaries, oceanic supply of nitrogen or phosphorus is sufficient that even with no TN or TP from the catchment, an A susceptibility band could not be obtained (in which case the minimum band is B). These are indicated by -. The last two columns give current annual TN and TP loads calculated using CLUES.

				Macroalgae TN ($t\ y^{-1}$)			Phytoplankton TN ($t\ y^{-1}$)			Phytoplankton TP ($t\ y^{-1}$)			Present load ($t\ y^{-1}$)	
Estuary ID	Estuary name	NZCHS class	Intertidal area (%)	A/B	B/C	C/D	A/B	B/C	C/D	A/B	B/C	C/D	TN	TP
49	Pakiri River	Tidal lagoon (permanently open)	35.24	**9.3**	**18.9**	**28.5**							18.438	4.528
50	Omaha Cove	Coastal embayment	0	6.7	14.0	21.4	**0.4**	**6.9**	**12.0**	**-**	**0.43**	**0.94**	1.547	0.251
51	Whangateau Harbour	Tidal lagoon (permanently open)	85.44	**99.6**	**210**	**321**	41.2	91.3	131	-	3.42	7.57	106.905	4.757
52	Millon Bay	Coastal embayment	61.55	17.9	37.8	57.6	**11.2**	**22.7**	**31.9**	**-**	**0.73**	**1.74**	4.300	1.310
53	Matakana River	Shallow drowned valley	75.98	**54.4**	**114**	**173**	58.3	93.6	122	-	2.21	5.09	40.983	7.804
78	Mahurangi Harbour System	Shallow drowned valley	51.18	**566**	**1188**	**1811**	327	944	1438	-	31.6	87.0	76.168	18.269
79	Te Muri-O-Tarariki	Tidal lagoon (permanently open)	99.93	**3.9**	**8.1**	**12.2**	2.7	4.1	5.1	-	0.11	0.25	3.348	1.177
80	Puhoi River	Tidal lagoon (permanently open)	70.58	**33.4**	**69.1**	**105**	19.2	42.8	61.7	-	1.25	3.15	30.793	10.869
81	Waiwera River	Tidal lagoon (permanently open)	64.49	**21.1**	**43.5**	**66.0**	9.9	22.4	32.4	-	0.73	1.84	27.119	6.656
82	Orewa River	Tidal lagoon (permanently open)	89	**20.4**	**42.4**	**64.4**	14.6	25.6	34.4	-	0.65	1.81	21.496	3.162
83	Okoromai Bay	Coastal embayment	27	23.8	50.0	76.1	**16.3**	**36.6**	**52.9**	**-**	**1.10**	**2.95**	1.117	0.130
84	Hobbs Bay (Gulf Harbour)	Coastal embayment	0	6.5	13.7	20.8	**1.9**	**6.5**	**10.1**	**-**	**0.24**	**0.66**	0.705	0.072
85	Weiti River	Tidal river mouth (spit enclosed)	63.04	**43.3**	**90.4**	**138**	35.0	58.1	76.6	-	1.31	3.72	19.158	2.436
86	Okura River	Tidal lagoon (permanently open)	79.27	**10.4**	**21.6**	**32.7**	11.2	17.5	22.6	-	0.40	1.06	9.115	1.081
90	Mangemangeroa Estuary WES	Shallow drowned valley	86.92	**11.4**	**23.7**	**35.9**	13.7	21.2	27.2	-	0.33	1.05	5.546	1.048
91	Turanga Creek WES	Shallow drowned valley	73.64	**24.5**	**51.0**	**77.6**	17.3	27.6	35.8	-	0.40	1.39	25.729	6.729
92	Waikopua Creek WES	Shallow drowned valley	99.97	**21.7**	**45.5**	**69.3**	16.7	28.0	37.0	-	0.41	1.54	12.897	1.773
93	Wairoa River	Shallow drowned valley	41.96	**95.4**	**195**	**295**	65.5	119	183	-	5.66	13.6	206.980	24.704
220	Waitakere River (Bethells Beach)	Beach Stream (stream with pond)	88.69	**9.8**	**19.2**	**28.5**							17.773	3.583
250	North Cove	Coastal embayment	37.32	11.2	23.6	36.0	**5.6**	**15.5**	**23.5**	**-**	**0.61**	**1.37**	0.395	0.039
251	Bon Accord Harbour	Coastal embayment	19.16	55.9	118	180	**8.8**	**49.4**	**81.8**	**-**	**2.80**	**6.45**	2.684	0.288

Estuary ID	Estuary name	NZCHS class	Intertidal area (%)	Macroalgae TN (t y^{-1}) A/B	B/C	C/D	Phytoplankton TN (t y^{-1}) A/B	B/C	C/D	Phytoplankton TP (t y^{-1}) A/B	B/C	C/D	Present load (t y^{-1}) TN	TP
252	South Cove Harbour	Coastal embayment	30.59	5.3	11.2	17.0	**3.4**	**7.4**	**10.6**	-	**0.28**	**0.64**	0.475	0.041
253	Gardiner Gap	Coastal embayment	59.61	5.6	11.8	18.0	**5.4**	**9.2**	**12.3**	-	**0.20**	**0.59**	0.638	0.099
254	Islington Bay	Coastal embayment	6.94	48.9	103	156	**16.9**	**55.6**	**86.5**	-	**1.42**	**4.58**	0.331	0.051
255	Matiatia Bay	Coastal embayment	2.86	10.2	21.5	32.7	**2.9**	**10.5**	**16.5**	-	**0.33**	**0.95**	0.291	0.042
256	Owhanake Bay	Coastal embayment	2.3	7.7	16.1	24.6	**1.1**	**4.5**	**7.3**	-	**0.20**	**0.55**	0.175	0.022
257	Oneroa Bay	Coastal embayment	0.66	41.1	86.3	131	**2.7**	**24.4**	**41.7**	-	**1.18**	**3.26**	0.398	0.046
258	Mawhitipana Bay	Coastal embayment	8.76	9.5	19.9	30.3	**1.5**	**8.7**	**14.5**	-	**0.34**	**0.94**	0.750	0.180
259	Te Matuku Bay	Coastal embayment	75.88	29.5	61.7	93.9	**15.0**	**25.1**	**33.2**	-	**0.60**	**1.70**	3.359	0.642
260	Awaawaroa Bay	Coastal embayment	28.73	73.0	153	233	**33.4**	**92.5**	**140**	-	**2.81**	**8.60**	5.666	1.322
261	Rocky Bay	Coastal embayment	30.43	31.1	65.3	99.4	**11.9**	**30.5**	**45.3**	-	**0.84**	**2.55**	1.740	0.212
262	Putiki Bay	Coastal embayment	35.45	80.4	169	257	**25.6**	**60.0**	**87.4**	-	**1.57**	**4.68**	5.705	0.435
263	Huruhi Bay	Coastal embayment	11.68	124	262	399	**19.1**	**93.1**	**152**	-	**3.78**	**11.6**	1.550	0.143
264	Tryphena Harbour	Coastal embayment	4.12	133	282	431	-	**63.0**	**117**	-	**6.67**	**13.8**	3.475	0.509
265	Blind Bay	Coastal embayment	5.27	59.7	127	194	-	**40.1**	**73.5**	-	**3.63**	**7.40**	3.108	0.342
266	Whangaparapara Harbour	Coastal embayment	13.79	36.2	76.7	117	-	**16.0**	**29.3**	-	**1.71**	**3.44**	1.801	0.255
267	Port Fitzroy/Port Albercrombie	Deep drowned valley	3.23	382	813	1244	-	**354**	**665**	-	**31.5**	**63.2**	9.026	1.268
268	Katherine Bay	Coastal embayment	3.33	69.6	148	226	**0.13**	**47.1**	**84.6**	-	**3.81**	**7.58**	4.602	0.628
269	Rangiwhakaea Bay	Coastal embayment	1.61	17.8	37.9	57.9	**0.04**	**9.8**	**17.7**	-	**0.77**	**1.52**	1.712	0.218
270	Whangapoua Creek	Tidal lagoon (permanently open)	93.97	**30.3**	**64.0**	**97.6**	18.6	33.1	44.7	-	1.56	3.01	5.418	0.802
271	Awana Bay	Beach Stream (stream with pond)	45	**4.8**	**9.8**	**14.9**							4.906	0.563
272	Kaitoke Creek	Beach Stream (stream with pond)	30.51	**8.2**	**16.7**	**25.2**							7.349	0.901
87	Waitematā Harbour System	Shallow drowned valley	36.16	**1854**	**3885**	**5916**	353	1376	2195	-	31.6	120	357.992	26.712
88	Tāmaki River	Shallow drowned valley	40	**390**	**817**	**1245**	106	254	373	-	6.33	22.5	91.092	6.611

3.6 Manukau Harbour nutrient model results

3.6.1 Predicted TN and TP distributions in Manukau Harbour

Modelled TN concentrations are highest (>1 mg/L) in the inner parts of Clarks Creek, Pahurehure Inlet, Taihiki River, and near the discharge of the Māngere Wastewater Treatment Plant (WWTP) (Figure 3-3). Away from these regions, TN concentrations are generally below 200 mg m^{-3}, although the discharge from the Māngere WWTP can be seen following the estuary channels towards the harbour mouth, as well as affecting the Māngere Inlet.

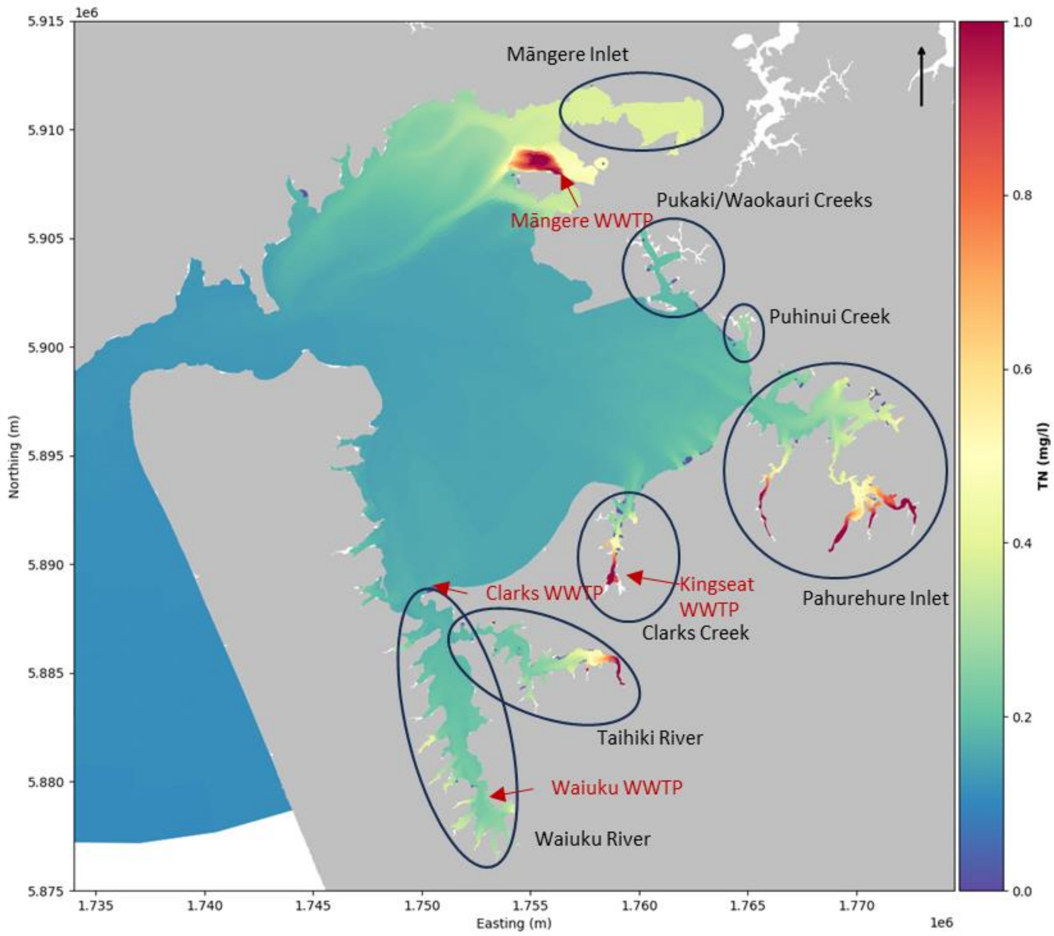

Figure 3-3: Modelled distribution of water column Total Nitrogen (TN) in Manukau Harbour. The colours show the modelled TN concentrations averaged over a spring-neap period for median stream flows and concentrations. The approximate boundaries of each subzone are indicated by the ovals (see Figure 2-4 for the actual boundaries used).

Modelled TP concentrations are dominated by the Māngere WWTP discharge, with the highest concentrations occurring around the discharge point as well as in Māngere Inlet (Figure 3-4). Like TN, the plume of high TP concentration follows the estuary channels towards the harbour mouth. TP concentrations are also locally elevated in the inner parts of Pahurehure Inlet and Clarks Creek; this is associated with the Kingseat WWTP.

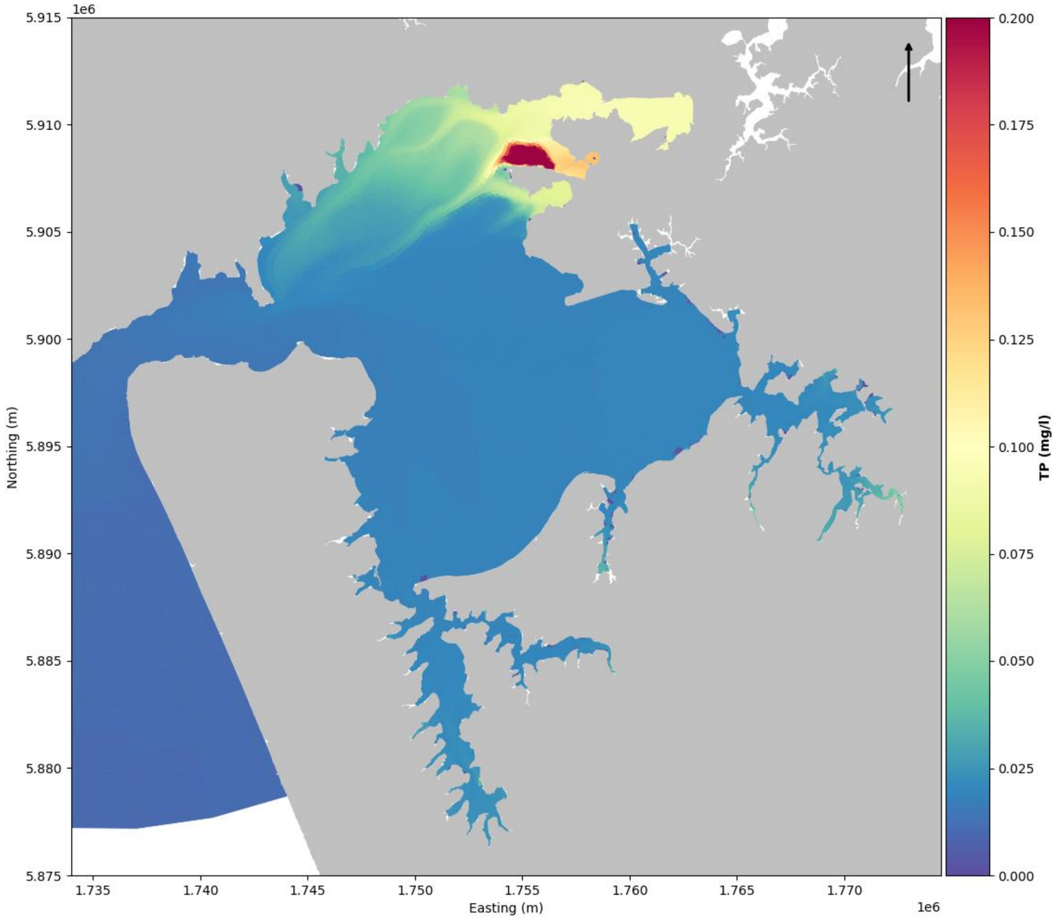

Figure 3-4: Modelled distribution of water column Total Phosphorus (TP) in Manukau Harbour. The colours show the modelled TP concentrations averaged over a spring-neap period for median stream flows and concentrations.

Potential TN and TP concentrations averaged within each estuary subzone (see Figure 2-4) are shown in Figure 3-5. The Clarks Creek subzone has the highest average TN concentration of 0.507 mg/L, followed by Māngere Inlet at 0.418 mg/L and Pahurehure Inlet at 0.351 mg/L. Note that the Māngere Inlet zone does not cover the embayment where the Māngere WWTP discharges, which is where TN concentrations are predicted to be highest (Figure 3-3).

The zone-averaged TN concentrations would indicate that Clarks Creek is likely in the ETI band D for macroalgal susceptibility, while Māngere Inlet and Pahurehure Inlet lie in band C (see Table 2-1 for TN concentrations corresponding to macroalgal susceptibility bands). The other subzones (Taihiki Inlet, Puhinui, Pukaki, Waiuku) have TN concentrations consistent with band B, while the central Manukau estuary zone have TN concentrations consistent with band A. However, the potential TN concentrations in Figure 3-5 are not directly comparable to the ETI Tool 1 macroalgal band thresholds in Table 2-1. The ETI band thresholds were derived from annual nutrient loads from the CLUES model, mean flows, and modelled potential TN concentration at high tide as these were the only data available across all NZ estuaries. For modelling we used median flows and concentrations for each source, and averaged over a spring-neap cycle as we believe this is more representative of 'typical' conditions. Consequently, TN concentration bands corresponding to macroalgal susceptibility bands may need adjustment to be comparable to concentrations derived from hydrodynamic modelling as done here.

Modelled TP was highest in Māngere Inlet (0.104 mg/L), and generally low (<0.024 mg/L) elsewhere in the estuary.

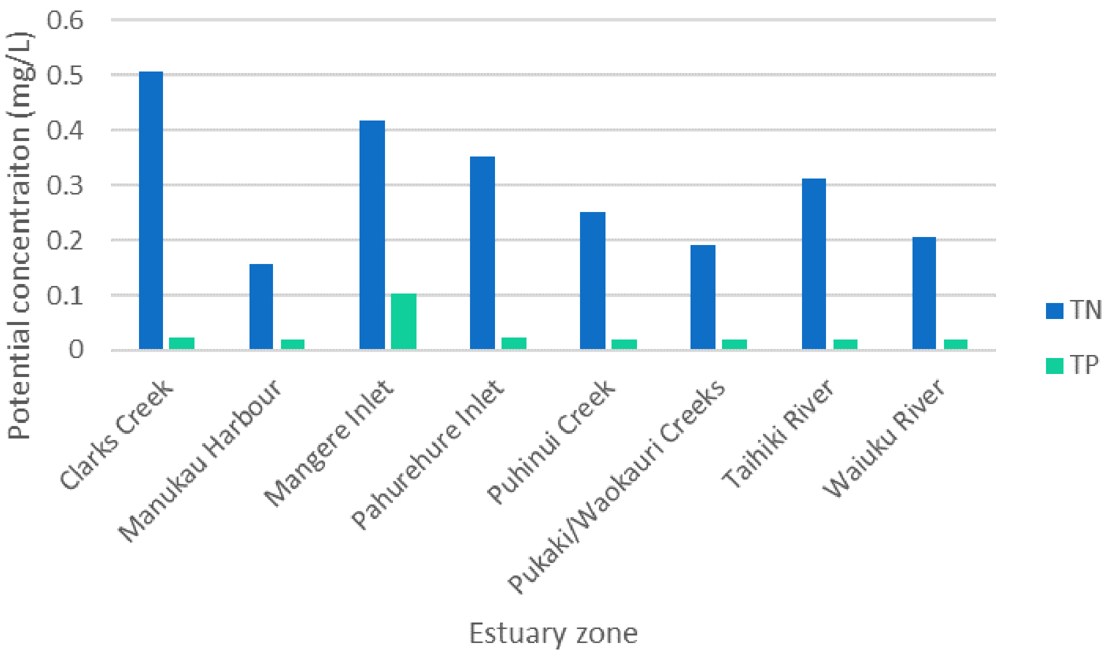

Figure 3-5: Time and spatially averaged total nitrogen (TN) and total phosphorus (TP) concentrations in each estuary sub-zone. See Figure 2-4 for delineation of each subzone.

The use of unique tracers for each source of freshwater input in the model allows nutrients within each zone to be attributed to their main sources. This is presented for each sub-zone in the following sections.

3.6.2 Comparison to observed nutrient concentrations

Locations and site numbers of water quality monitoring sites in Manukau Harbour are shown in Figure 3-6, and mean TN and TP concentrations at these sites are compared to modelled concentrations in Figure 3-7.

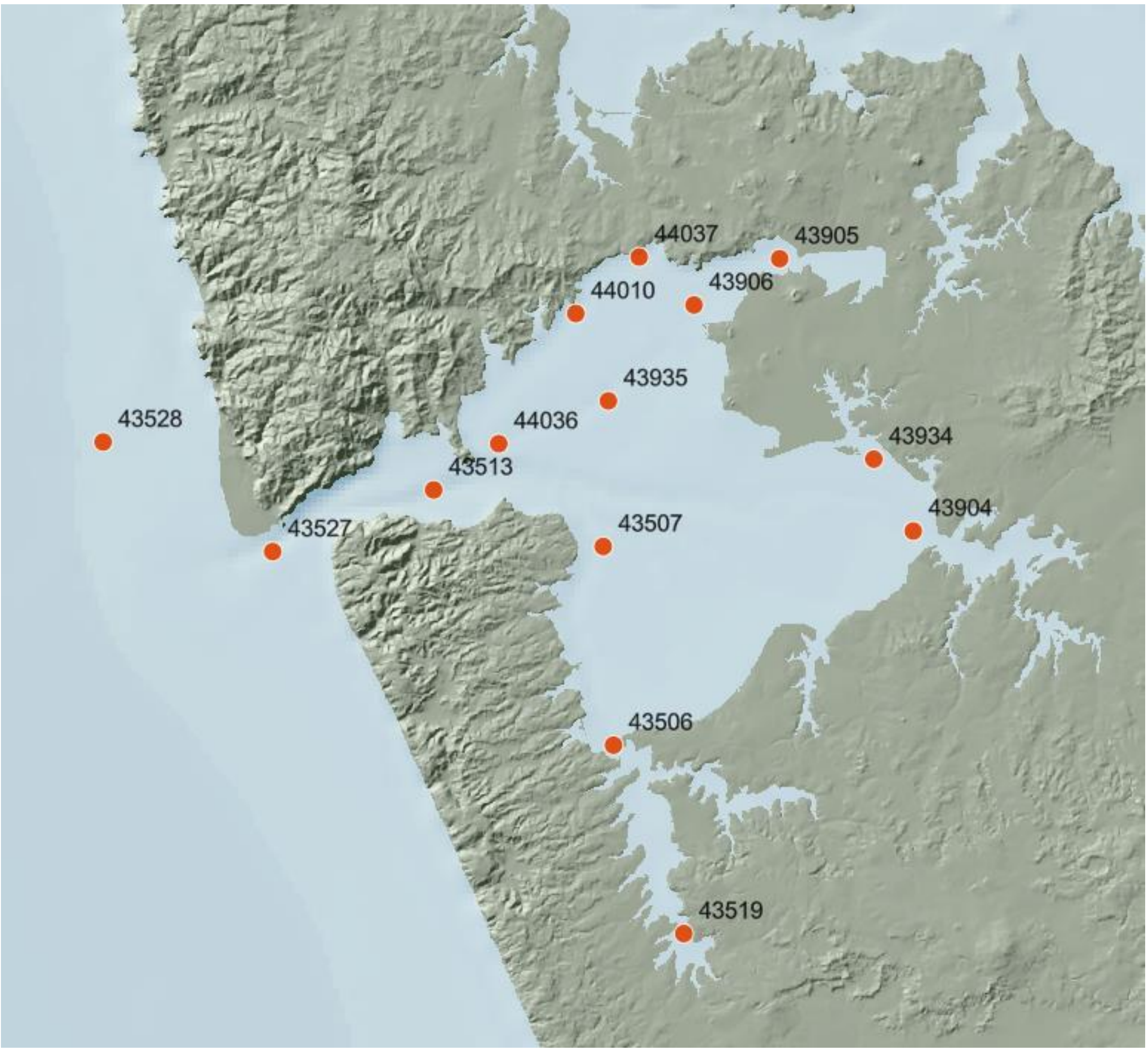

Figure 3-6: Monitoring sites in Manukau Harbour. Mean values of total nitrogen (TN) and total phosphorus (TP) were calculated for each site from data across the entire available date range, and from data collected between 01/01/2013 and 01/01/2018.

There is generally good agreement between observed and modelled TN concentrations, although the model tends to underestimate TN at the inner most sites close to major sources such as in Māngere Inlet, Pahurehure Inlet and Waiuku River. TP is underpredicted at all sites other than those nearest the entrance, suggesting that phosphorus inputs to the estuary are underestimated, perhaps by ~30%. However, the spatial distributions of TN and TP agree well with observations indicating that the transport of nutrients is modelled well, although the nutrient loads (particularly for TP) may be underestimated.

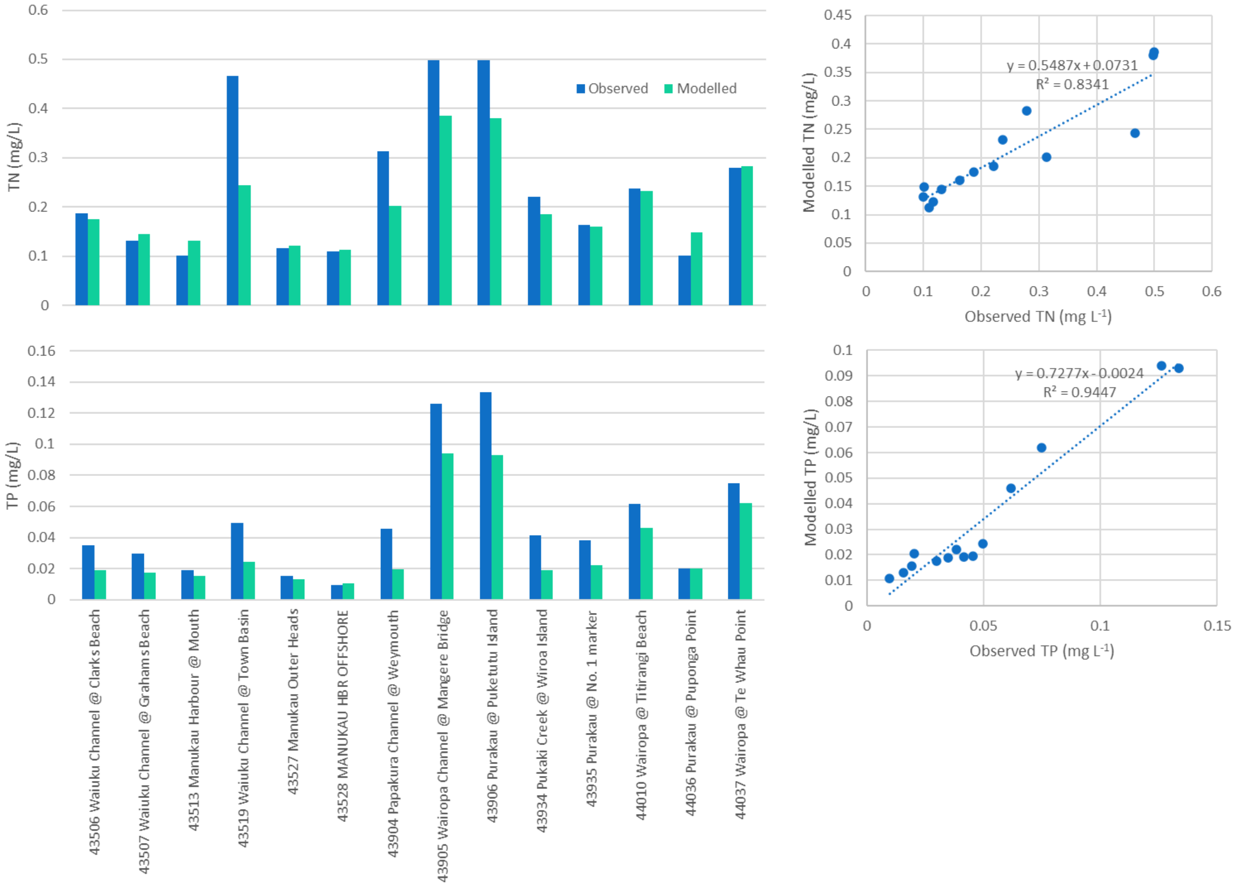

Figure 3-7: Comparison between observed and modelled TN and TP in the Manukau Harbour. Shown are comparisons between modelled values and mean measured TN and TP values calculated for each site from the entire available data record.

3.6.3 Manukau Harbour zone

The Manukau Harbour zone covers the entire harbour except for those areas included in any of the other subzones (see Figure 2-4). The ocean (68%) and Māngere WWTP (20%) are the largest sources of TN in this zone (Figure 3-8). The next largest source is streams in the Pahurehure Inlet (collectively 6%), particularly Whanagapouri Creek and Ngakoroa Stream. Discharges from streams in the Taihiki, Waiuku and Clarks Creek zones are collectively responsible for a further 5% (~1–2% attributable to each zone), while the remaining ~1% of TN originates largely from streams discharging directly to the Manukau Harbour proper (the inputs from the Māngere zone, Pukaki zone and other WWTP are all less than 1%).

The Māngere WWTP is the largest source of TP (49%), followed by the ocean (48%). Collectively, inputs from all streams contribute ~2% of TP with most of that coming from the Pahurehure Inlet zone.

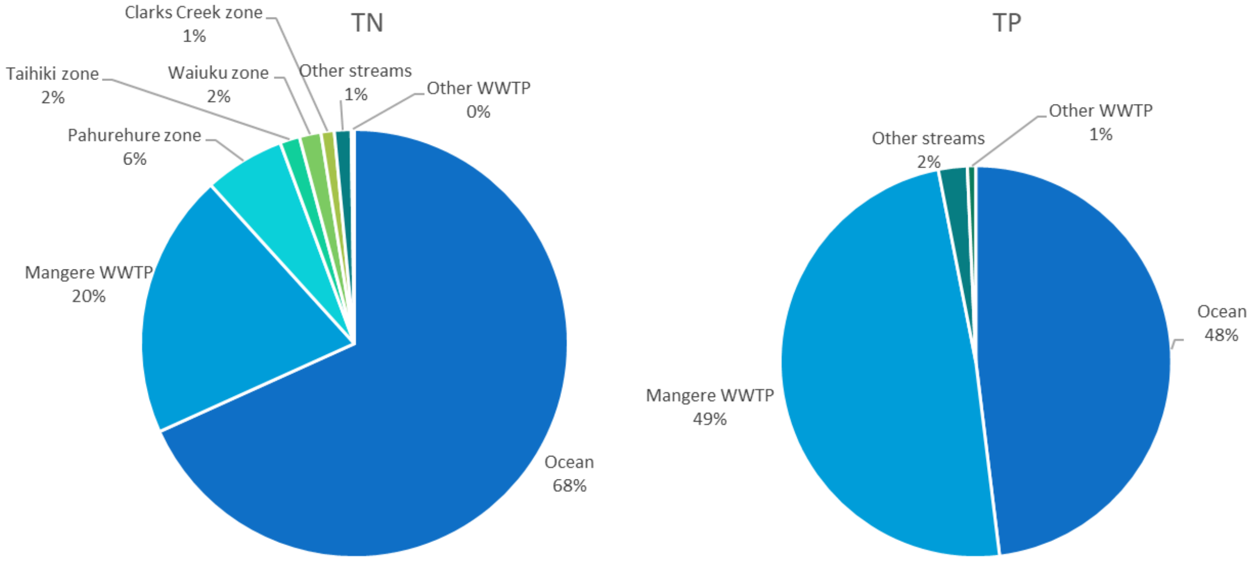

Figure 3-8: Sources of Total Nitrogen (TN) and Total Phosphorus (TP) in the Manukau Harbour zone.

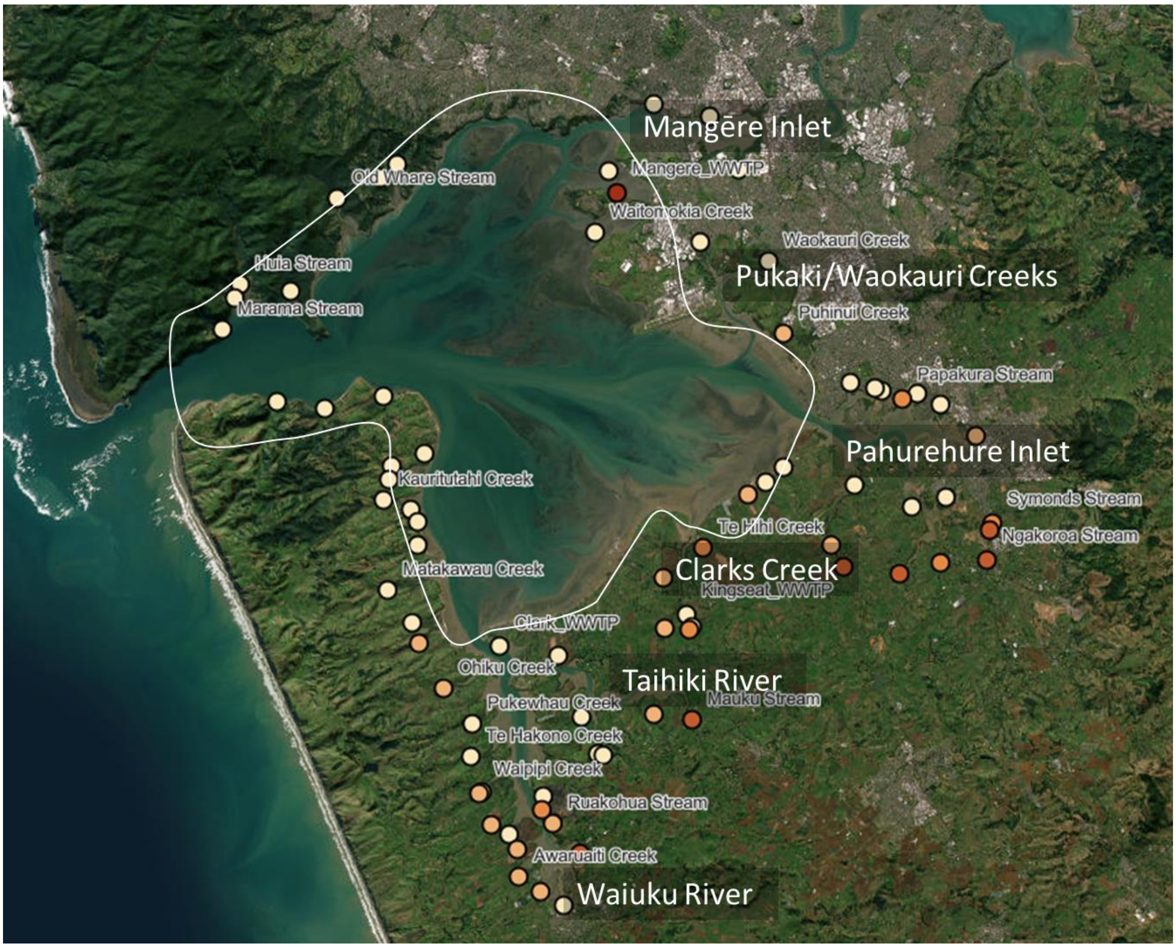

Figure 3-9: Locations of the sources of Total Nitrogen to the Manukau Harbour zone (outlined by the white polygon). Points marking terminal reaches are coloured by their relative contribution of TN to the Manukau Harbour zone from white to red, with increasing redness indicating increasing contributions.

3.6.4 Māngere Inlet zone

The Māngere WWTP is the largest source (70%) of TN to the Māngere Inlet (Figure 3-10). The second largest source of TN is the ocean (25%). The total input of TN from all streams in the Māngere Inlet contributes only 1% of TN, similar to what originates from the Pahurehure Inlet (~2%). All other streams in the harbour are responsible for 2% of TN in this zone.

The Māngere WWTP is also the dominant source of TP (90%), with small portions coming from the ocean (9%) and all freshwater inputs to the harbour combined (1%).

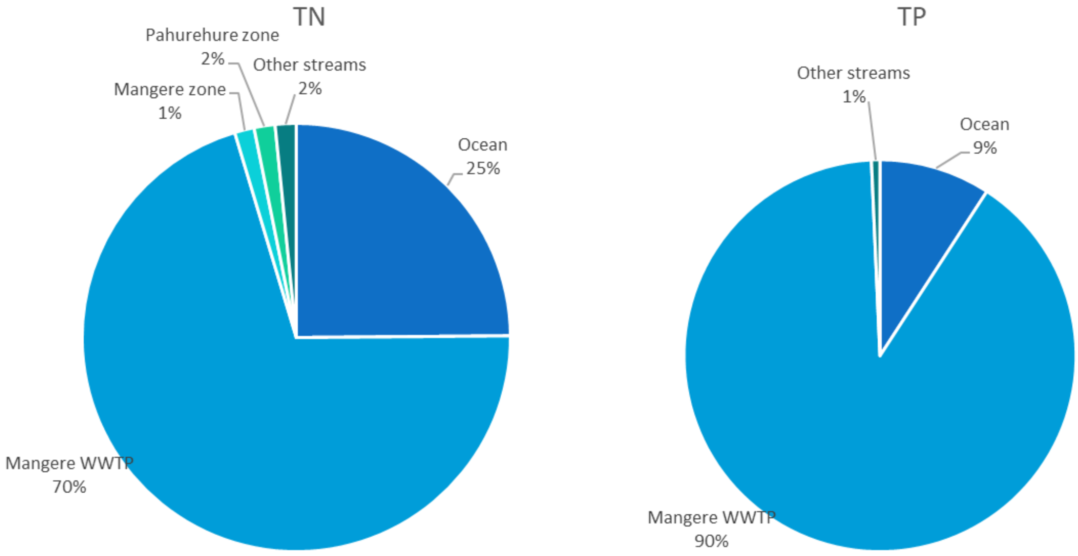

Figure 3-10: Sources of Total Nitrogen (TN) and Total Phosphorus (TP) in the Māngere Inlet zone.

3.6.5 Pukaki/Waokauri Creeks zone

The ocean is the single largest source of TN (55%) and TP (50%) to the Pukaki/Waokauri Creeks zone (Figure 3-11). The largest non-oceanic source is the Māngere WWTP (12% TN, 39% TP). The streams within the Pukaki/Waokauri zone contribute around 3% of TN, which is small compared to the impact of inputs from streams in the Pahurehure zone, particularly the Ngakoroa Stream, Whangapouri Creek, Whangamaire Stream, and Hingaia Stream which collectively contribute 16% of TN. Other streams in Pahurehure Inlet contribute 7% of TN, while all other streams in the Manukau Harbour are responsible for the remaining 7% of TN.

Phosphorus concentrations are dominated by the ocean (50%) and Māngere WWTP (39%). Similarly to TN, streams in the Pahurehure Inlet are the other significant source, contributing to 7% of the TP concentration in the Pukaki/Waokauri Creeks zone, while streams within the Pukaki/Waokauri zone contribute only 2% of TP.

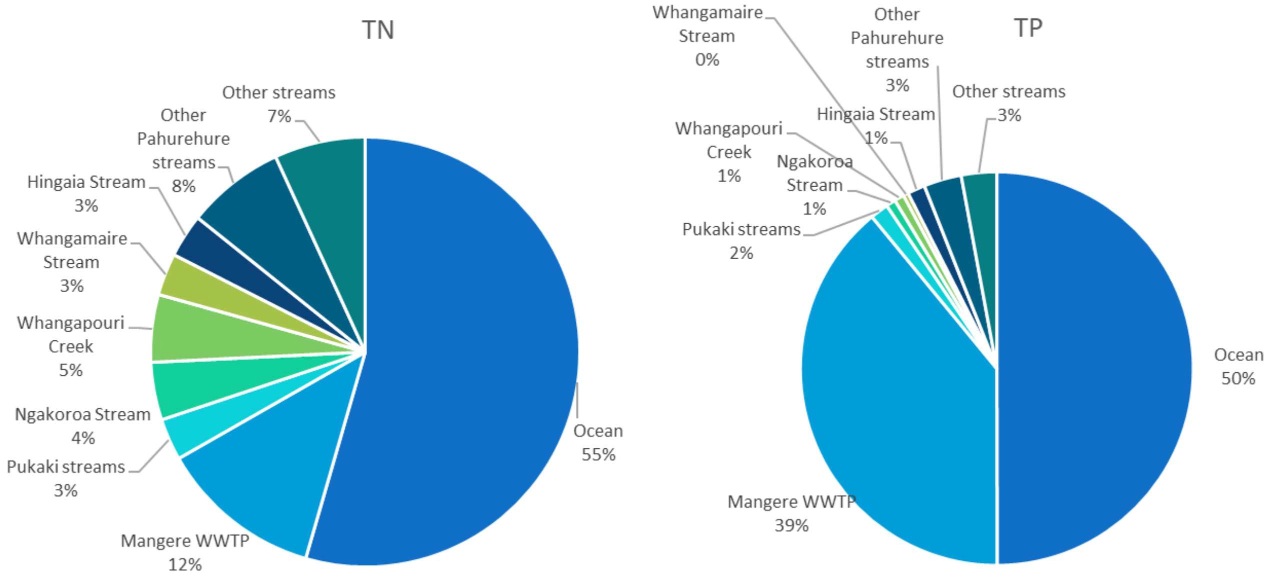

Figure 3-11: Sources of TN and TP in the Pukaki/Waikauri Creek zone.

3.6.6 Puhinui Creek zone

After the ocean (38% of TN) the largest contributor of TN to the Puhinui Creek zone is Puhinui Creek (28%, Figure 3-12). Streams in the Pahurehure Inlet contribute 22% of TN, with the Whangapouri Creek, Ngakora Stream, Hingaia Stream and Whangamaire Stream being the main sources. The Māngere WWTP contributes a further 9%. The major sources of TP are the ocean (41%), Māngere WWTP (32%) and Puhinui Creek (18%).

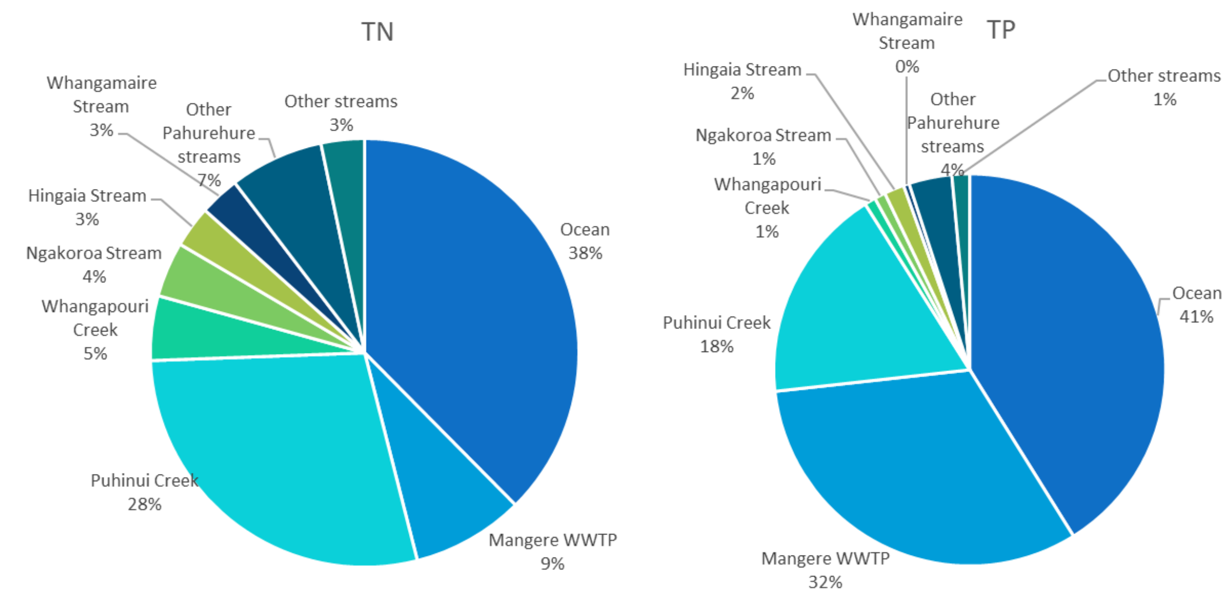

Figure 3-12: Sources of TN and TP in the Puhinui Creek zone.

3.6.7 Pahurehure Inlet zone

TN in the Pahurehure Inlet zone largely comes from the streams that discharge into this inlet (collectively contributing 64% of TN, (Figure 3-13). The main sources of TN are the Ngakoroa Stream, Whangapouri Stream, Whangamaire Stream and the Hingaia Stream. The ocean supplies around a quarter (27%) and Māngere WWTP 6% of TN to this zone.

TP largely comes from outside the Pahurehure Inlet, with the ocean (40%) and Māngere WWTP (31%) being the largest sources. Streams discharging to the Pahurehure Inlet collectively contribute 27% of TP, with the Hingaia Stream being the single largest local source.

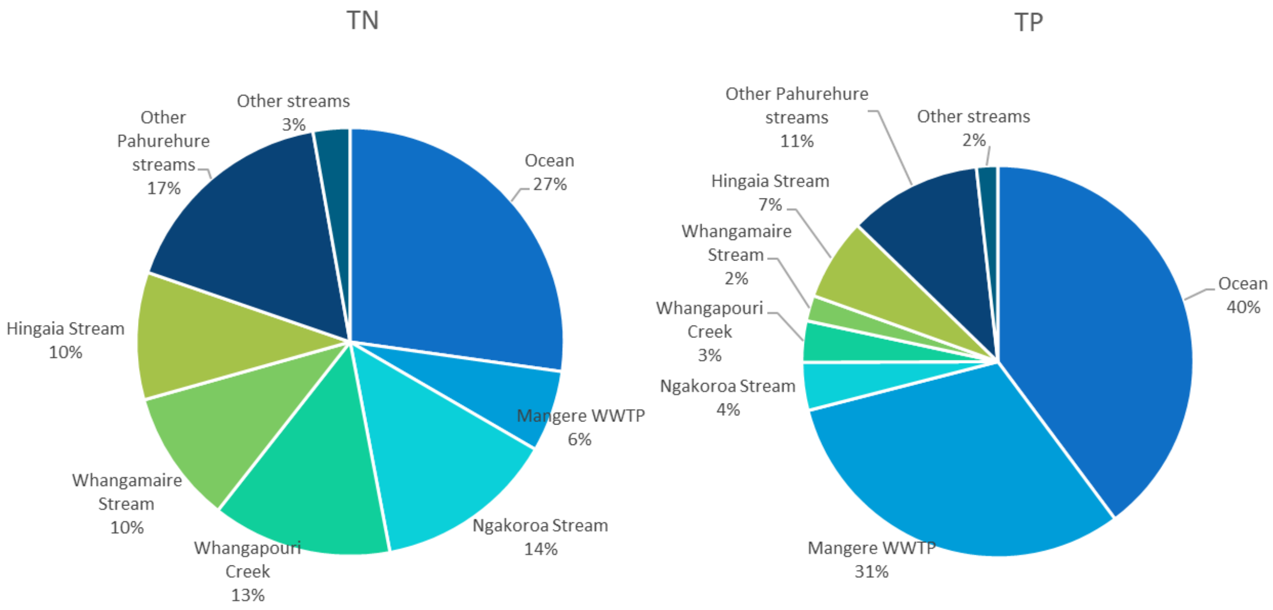

Figure 3-13: Sources of TN and TP in the Pahurehure Inlet zone.

3.6.8 Clarks Creek zone

The majority (71%) of the TN found in Clarks Creek originates from the streams discharging into the Clarks Creek zone (Figure 3-14). Puhitahi Creek, at the head of Clarks Creek, is the single largest source of TN (36%), followed by Karaka Creek and Te Hihi Creek. Other streams elsewhere in the harbour are responsible for ~6% of TN, while the ocean provides 19% and the Māngere WWTP a further 4%.

After the ocean (37% TP), the single largest source of total phosphorus is the Māngere WWTP (29%), with local streams contributing another 29%, and the remainder comes from other streams discharging to the harbour.

The Kingseat WWTP appears to have negligible effect on TN and TP concentrations in the Clarks Creek zone.

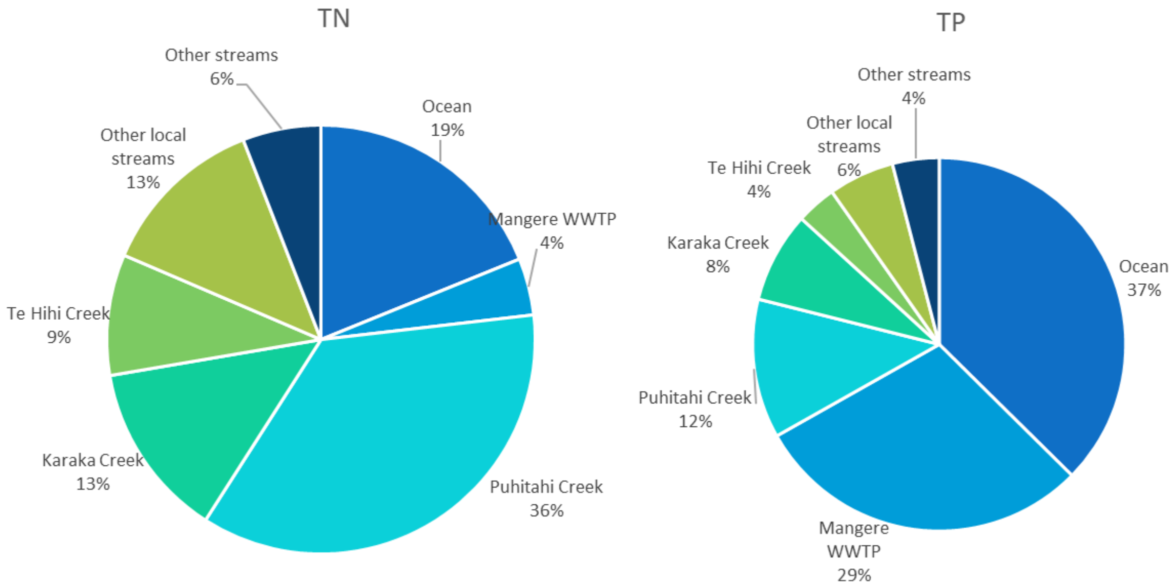

Figure 3-14: Sources of Total Nitrogen (TN) and Total Phosphorus (TP) in the Clark Creek zone.

3.6.9 Taihiki River zone

The main source of TN in the Taihiki River zone is the Mauku Stream, contributing 72% of TN (Figure 3-15). Other streams in the Taihiki River zone provide another 8%, while 10% comes from streams elsewhere in the harbour. The Mangerē WWTP contributes around 7% of TN, while other WWTP (particularly the Waiuku WWTP) contribute ~1% of TN.

Nearly half of TP comes from the ocean (47%) while the Māngere WWTP is responsible for another third (33%). Local streams provide another 10%. Other WWTP contribute 5% of TP, nearly all of which comes from the Waiuku WWTP.

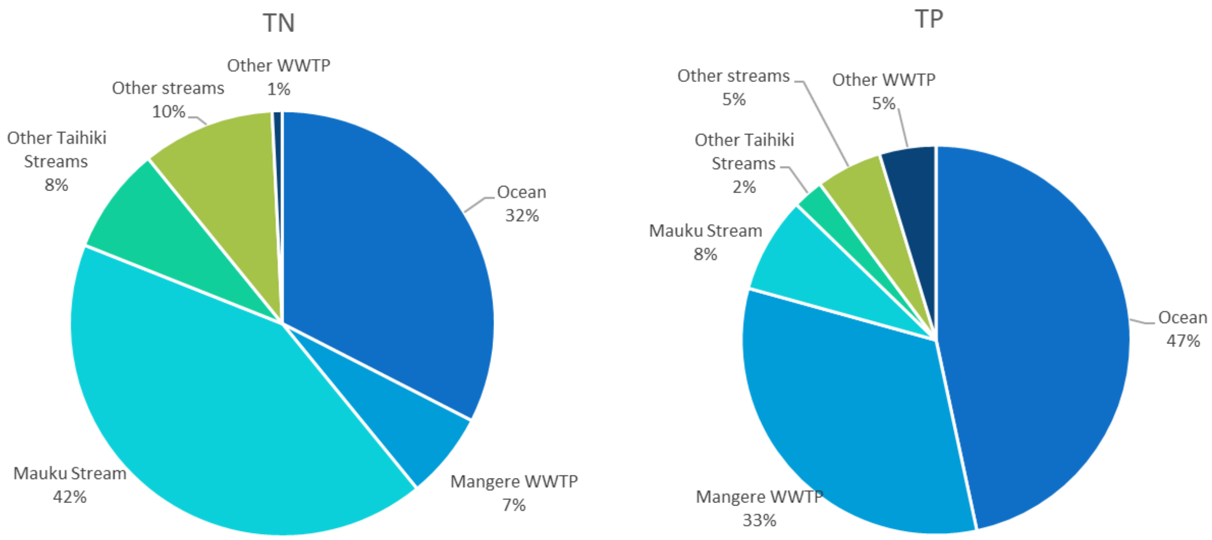

Figure 3-15: Sources of Total Nitrogen and Total Phosphorus in the Taihiki River zone.

3.6.10 Waiuku River zone

The ocean is the largest source of both TN (46%) and TP (47%) to the Waiuku River zone. The streams within the Waiuku zone contribute 21% of TN, with the Waitangi Stream being the single largest input. Streams in the Taihiki zone contribute another 8% of TN, with most of that coming from the Mauku Stream.

After the ocean, the Mangerē WWTP is the single largest source of TP (33%), with other WWTP plants (particularly the Waiuku WWTP) contributing a further 10%.

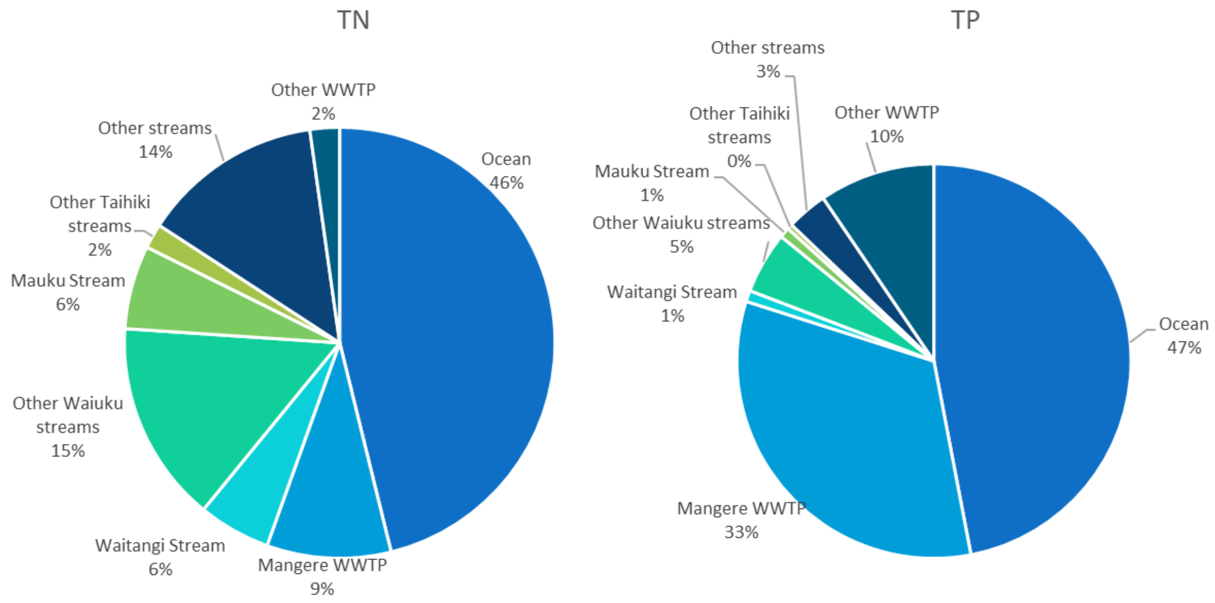

Figure 3-16: Sources of Total Nitrogen and Total Phosphorus in the Waiuku River zone.

3.7 Kaipara Harbour nutrient model results

3.7.1 Predicted TN and TP distributions in Kaipara Harbour

Total nitrogen concentrations are highest in the Wairoa arm of the Kaipara Harbour (Figure 3-17). This is due to the Wairoa River which is the biggest source of inflow to the Kaipara Harbour. TN concentrations are generally low (<0.200 mg/L) in the southern part of the harbour administered by Auckland Council, except near river mouths, particularly near the Kaipara and Hoteo Rivers. Concentrations are lowest near the harbour mouth.

The modelled potential TN concentrations are also compared with observed median TN concentrations at estuary sites monitored by Auckland Council and Northland Regional Council. The model generally captures the distribution patterns of TN, with highest concentrations near the major river mouths and decreasing towards the ocean; however, we note that the fits for the Kaipara harbour were not as good as those for the Manukau or Waitematā.

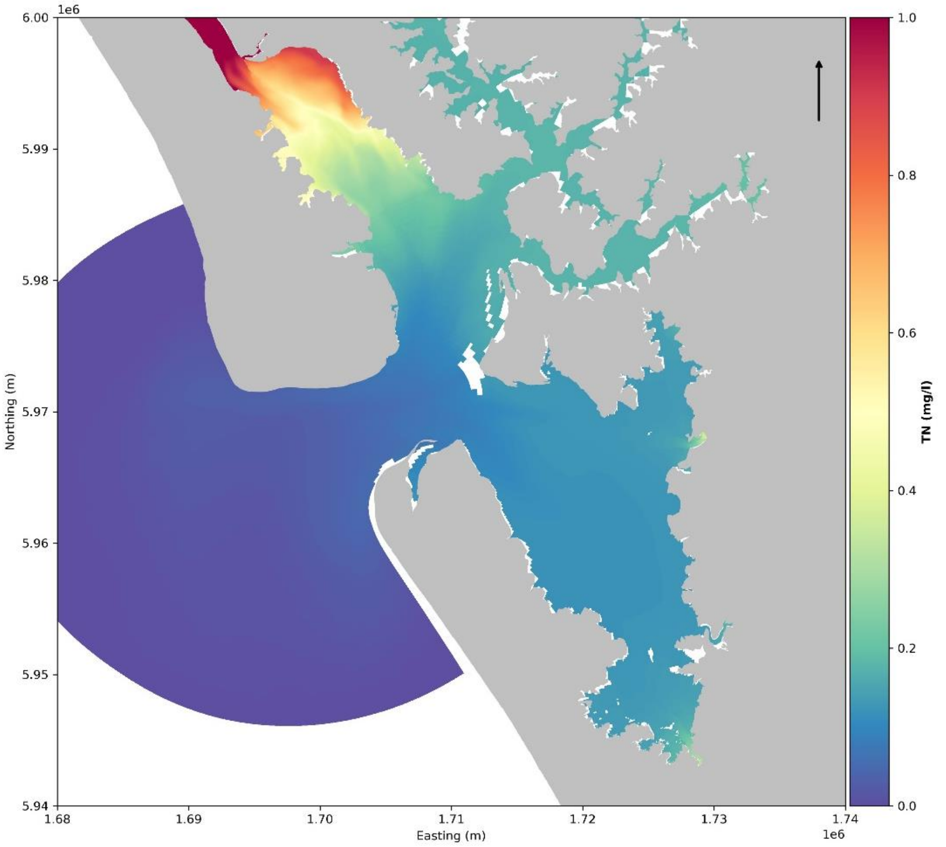

Figure 3-17: Distribution of modelled potential Total Nitrogen (TN) in Kaipara Harbour. The colours show the modelled TN concentrations averaged over a spring-neap period for median stream flows and concentrations.

Distributions of TP are broadly similar to those of TN, with highest TP concentrations near the Wairoa River, elevated concentrations near river mouths, and generally decreasing towards the harbour mouth (Figure 3-18). The model underestimates TP throughout the harbour, suggesting either the modelled TP catchment loads are too low, or that there is an unaccounted-for source of TP such as internal loading (phosphorus released from sediments) or resuspension.

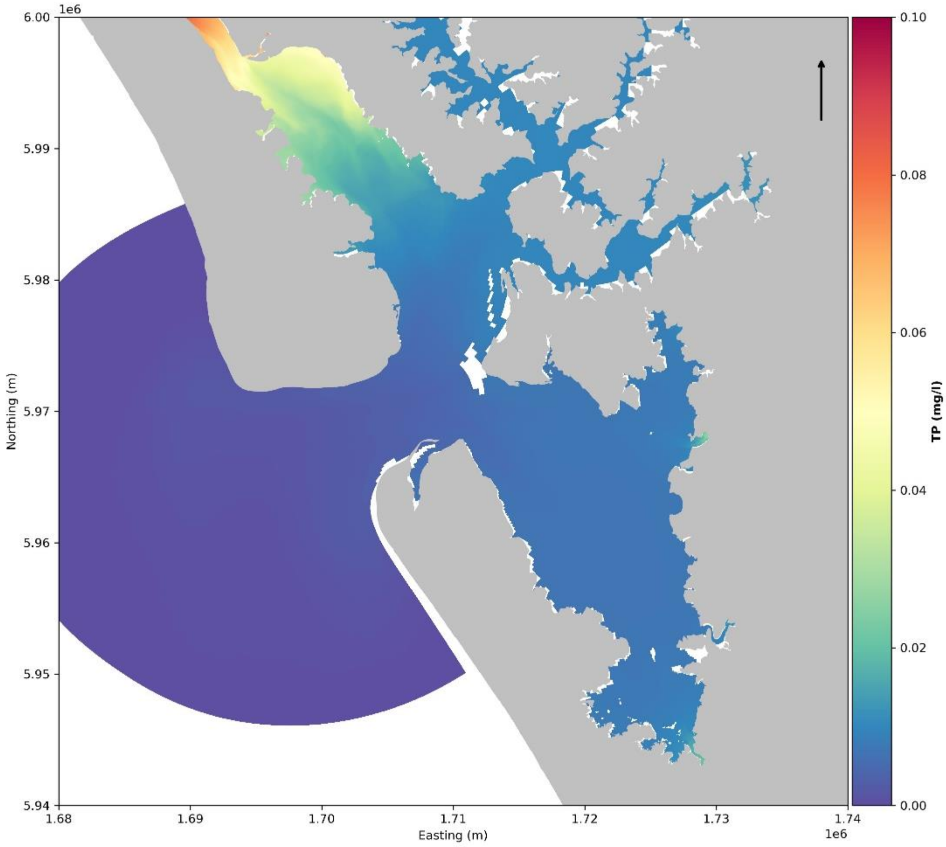

Figure 3-18: Distributions of modelled Total Phosphorus (TP) in Kaipara Harbour. The colours show the modelled TP concentrations averaged over a spring-neap period for median stream flows and concentrations.

For the subzones of the estuary defined in Figure 2-5 (see also Figure 3-20), concentrations of TN and TP are highest in the Hoteo Estuary zone (0.360 and 0.027 mg/L, respectively). All other zones have TN less than 0.220 mg/L and TP less than 0.017 mg/L.

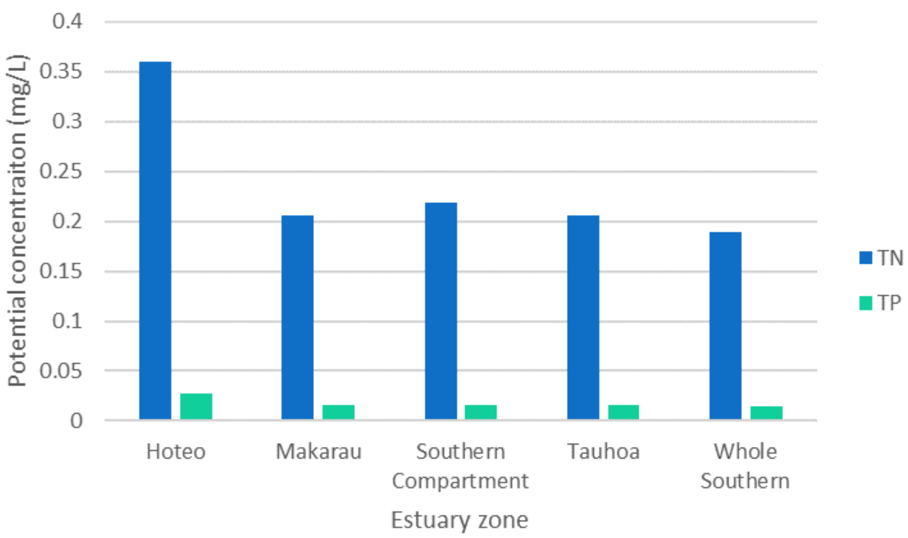

Figure 3-19: Time and spatially averaged total nitrogen (TN) and total phosphorus (TP) concentrations in each Kaipara Harbour estuary sub-zone. See Figure 2-5 for the boundaries of estuary subzones.

In the following subsections describing each estuary subzone, reference is made to various rivers that flow into the Kaipara Harbour. The location of the 20 river inflows included in the modelling, as well as the approximate boundaries of each sub-estuary or zone, are shown in Figure 3-20.

Figure 3-20: Locations of the terminal reaches for the rivers discharging to the Kaipara Harbour included in this study. Points are coloured by TN load, from white to red, with increasing redness indicating increasing loads. The yellow polygons indicate the sub-estuaries considered in this study. The dashed blue line between Okahukara Peninsula and South Head denotes the northern extent of the Central Kaipara South zone.

3.7.2 Comparison to observed nutrient concentrations

The locations and site numbers of water quality monitoring sites in the Kaipara Harbour are shown in Figure 3-21, and mean observed TN and TP concentrations compared to modelled concentrations in Figure 3-22.

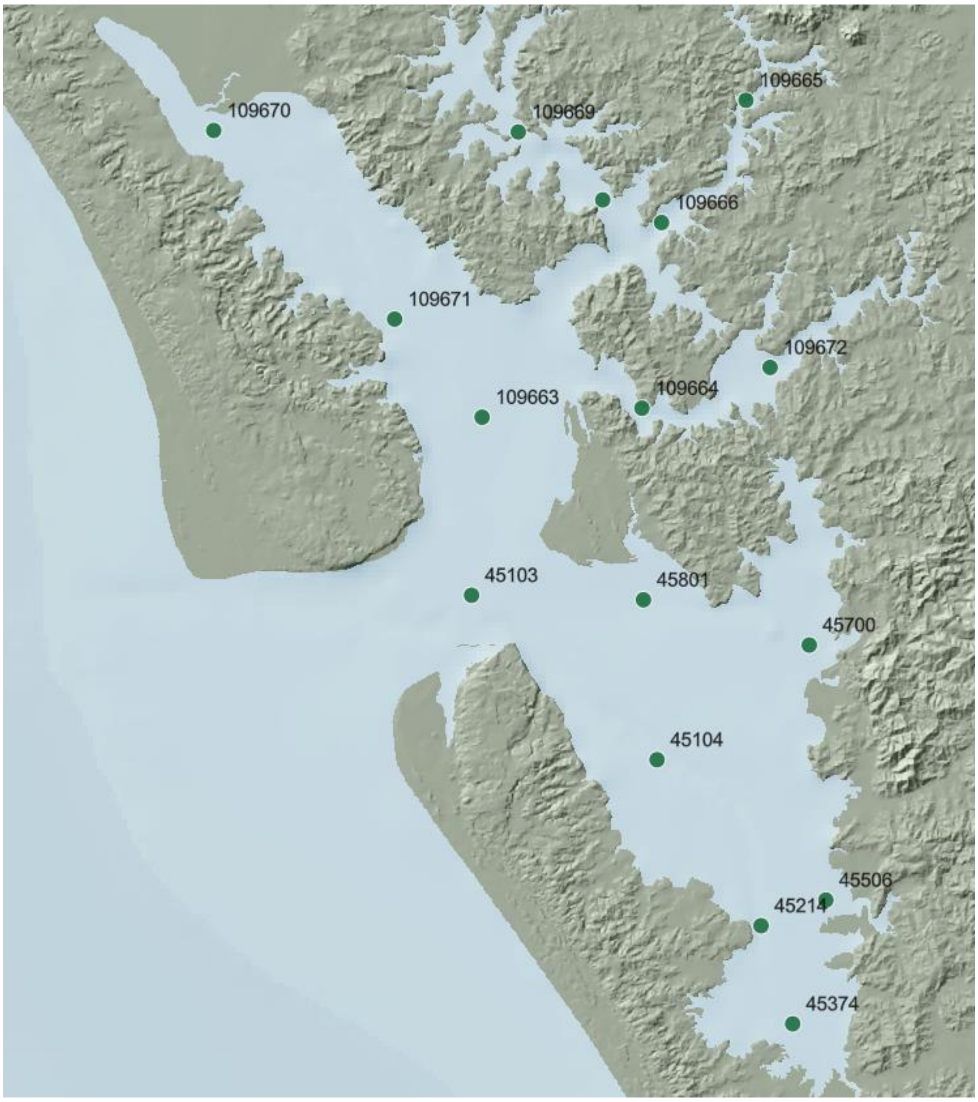

Figure 3-21: Monitoring sites in Kaipara Harbour. Mean values of total nitrogen (TN) and total phosphorus (TP) were calculated for each site from data across the entire available date range, and also from data collected between 01/01/2013 and 01/01/2018.

For TN, the model tends to underpredict in the southern part of the harbour and the upper Otamatea arm, and overpredict in the upper Oruawharo and Arapaoa arms. The model generally captures the relative differences in TN concentrations in the southern part of the harbour, though indicates that perhaps TN loads are underestimated in this part of the harbour. Phosphorus is underpredicted throughout the harbour suggesting either the catchment TP loads are underestimated, or there is a large unaccounted-for source of phosphorus such as internal loading.

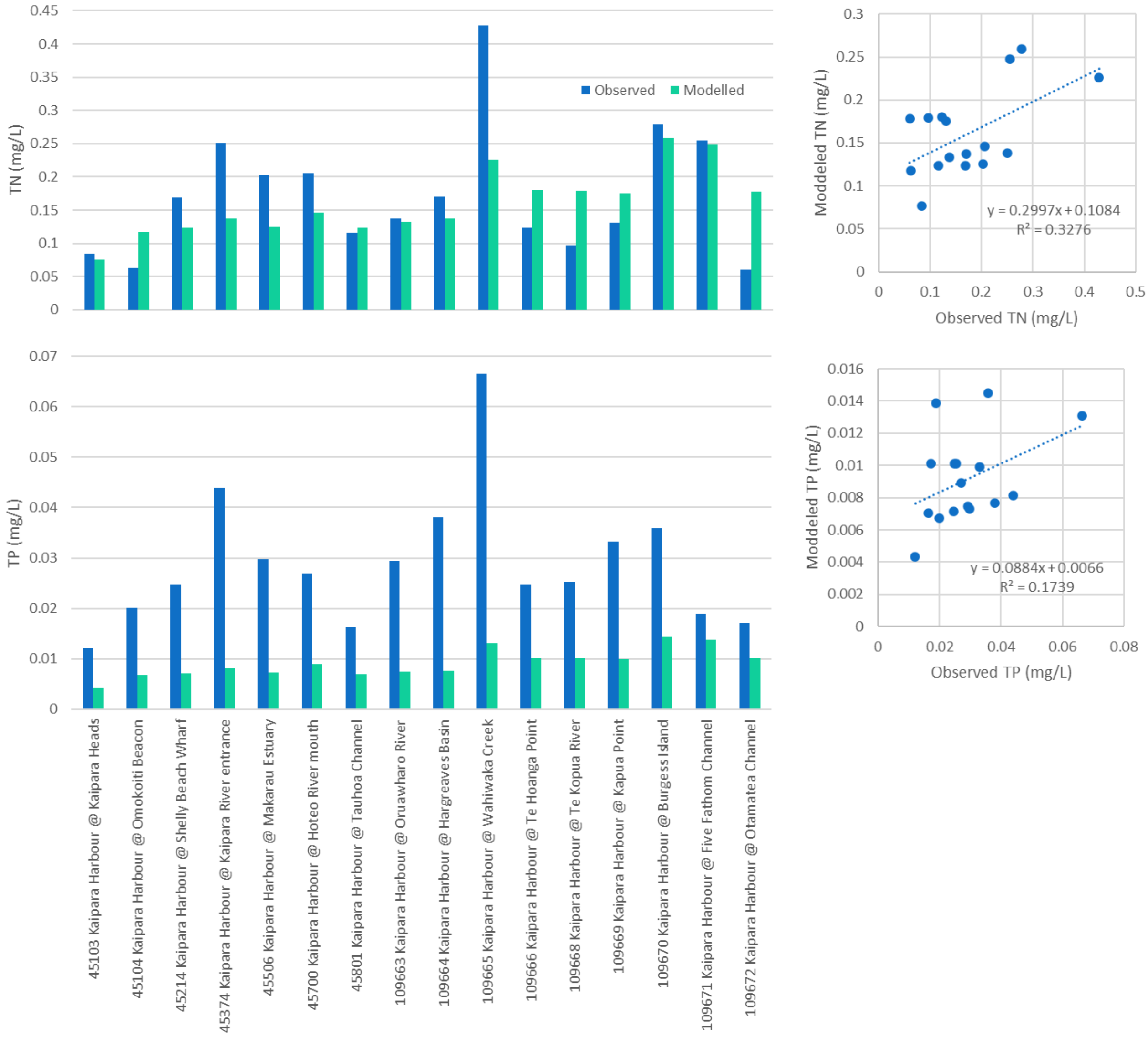

Figure 3-22: Comparison of observed and modelled TN and TP in Kaipara Harbour. Shown are comparisons between modelled values and mean measured TN and TP values calculated for each site from the entire available data record.

3.7.3 Central Kaipara South zone

Considering first the southern part of the Kaipara Harbour, which is the part of the estuary south of a line between Okahukara Peninsula and South Head but excludes the subzones in Figure 2-5, the ocean is the single largest source of TN (51%). The Wairoa River is the largest source of riverine TN (18%), followed by the Kaiwakawaka River (8%) which enters the central (eastern) part of the estuary. All other river inflows north of Manakapua Island contribute a further 6%, such that nearly a third (~32%) of TN in the southern part of the estuary comes from the northern or central parts of the estuary. Rivers in the southern estuary contribute ~17% of TN, with the major sources being the Kaipara River, Kaukapakapa River and Hoteo River. The modelling suggests that most of the TN in the southern part of the Kaipara Harbour comes either from the ocean or the central or northern part of the harbour.

The largest source of TP is the ocean (61%) followed by Wairoa River (15%). Around 15% of TP comes from rivers in the southern part of the estuary, and this is mostly from the Kaipara River, Kaukapakapa River and Hoteo River.

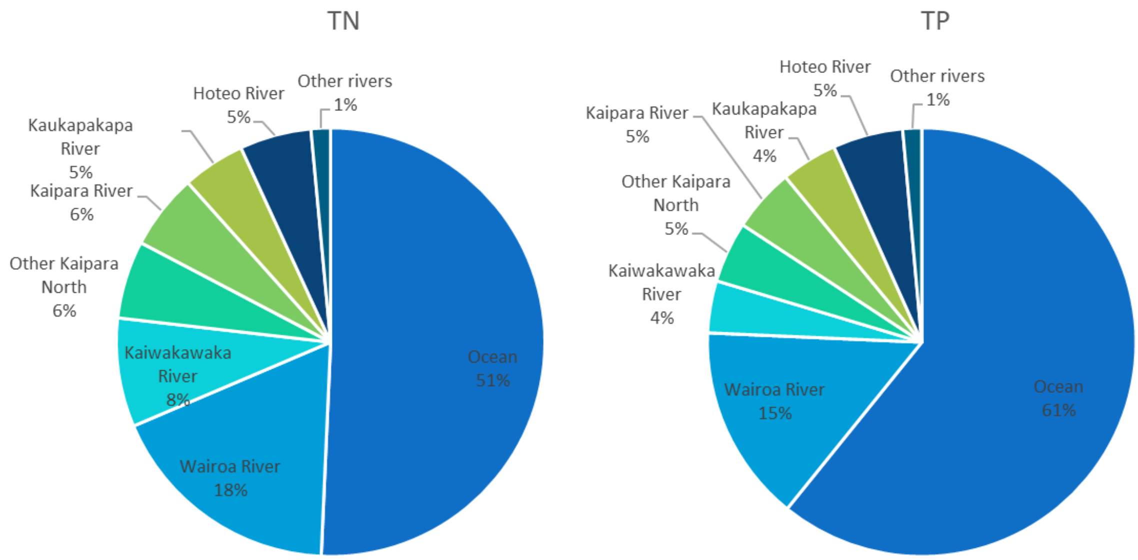

Figure 3-23: Sources of TN and TP in the Southern Kaipara Harbour.

3.7.4 Southern Compartment zone

The Southern Compartment is the part of the estuary south of Shelly Beach, and the major inflows in this region are the Kaipara River and Kaukapakapa River. Collectively, these two rivers contribute 26% of TN in the Southern Compartment, with a further 7% coming from other rivers in the estuary south of Okahukara Peninsula. Rivers in the northern part of the estuary contribute 26% of TN, with most of that coming from the Wairoa River (15%) and Kaiwakawaka River (6%). The ocean provides 41% of TN.

Sources of TP are in similar proportions to those of TN except that the ocean provides a larger portion of TP (50%) compared to TN (41%). The largest riverine sources of TP are the Kaipara River, Wairoa River and Kaukapakapa River.

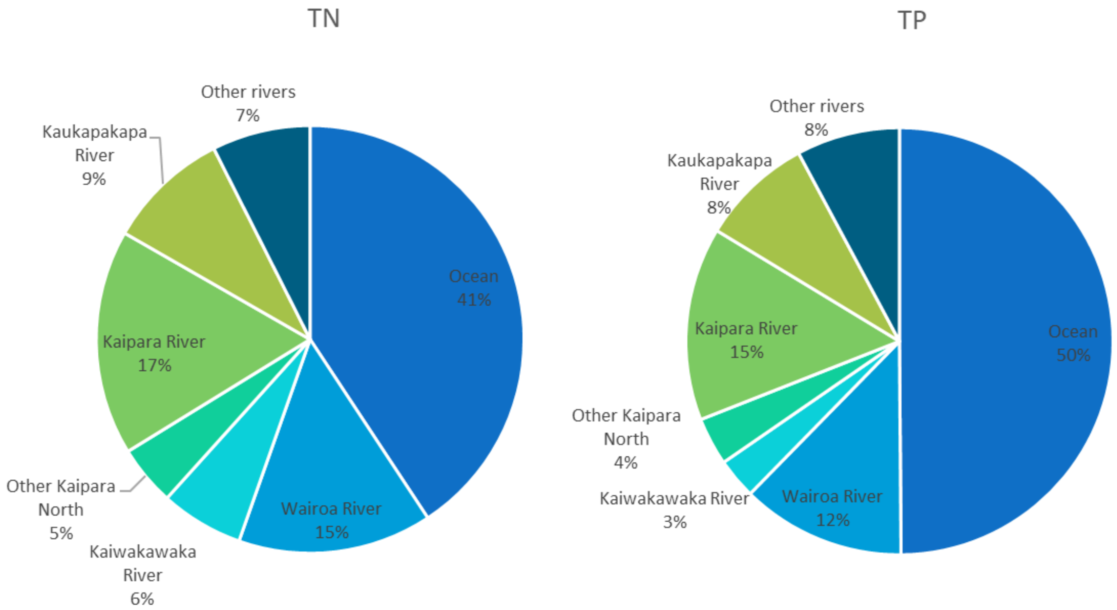

Figure 3-24: Sources of TN and TP in the Kaipara Harbour Southern Compartment.

3.7.5 Makarau Estuary zone

Rivers in the northern part of the Kaipara Harbour contribute about the same portion of TN to the Makarau Estuary as rivers in the south of the estuary (28% respectively), with the remainder originating from the ocean. The Makarau River is a relatively small source of TN in this zone, contributing 8%, similar to the Kaipara River (8%), Kaukapakapa River (5%) and the Kaiwakawaka River (7%). The single largest source of riverine TN in this zone is the Wairoa River (16%).

For TP, the ocean is the largest source (24%), followed by the Wairoa River (21%), Makarau River (13%) and Kaipara River (11%). About a third (32%) of TP originates from the northern part of the harbour (including the Wairoa and Kaiwakawaka Rivers), similar to the 31% of TP coming from rivers in the south of the Kaipara Harbour but outside of the Makurau Estuary.

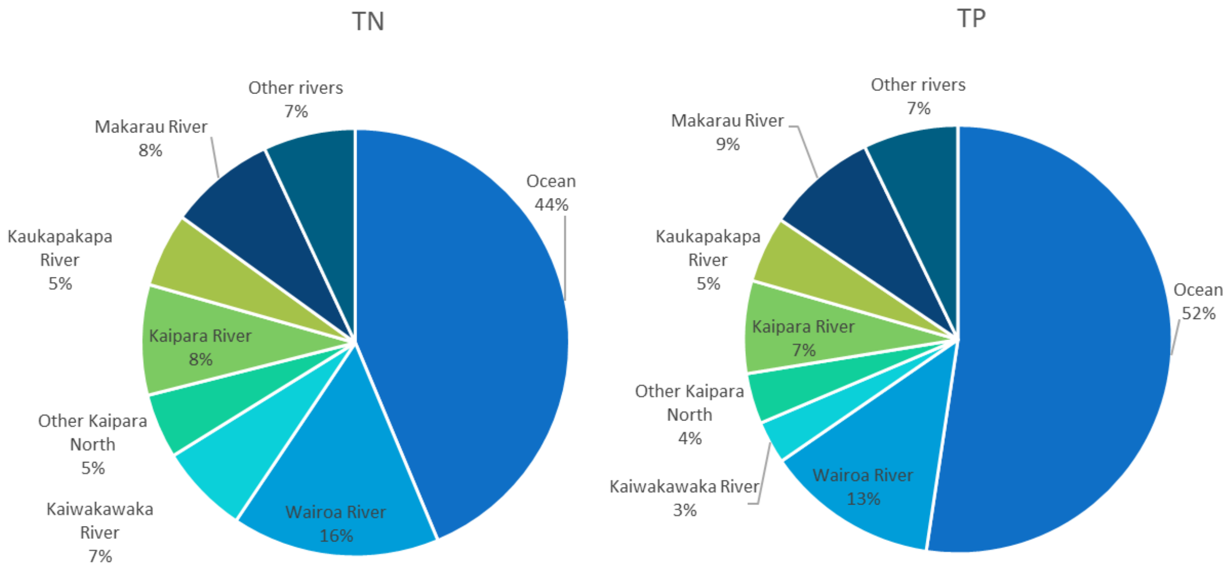

Figure 3-25: Sources of TN and TP in the Makarau Estuary.

3.7.6 Hoteo zone

The Hoteo zone is a relatively small part of the Kaipara Harbour extending upstream of Breach Point. Both TN and TP are dominated by inputs from the Hoteo River (68% of TN and TP).

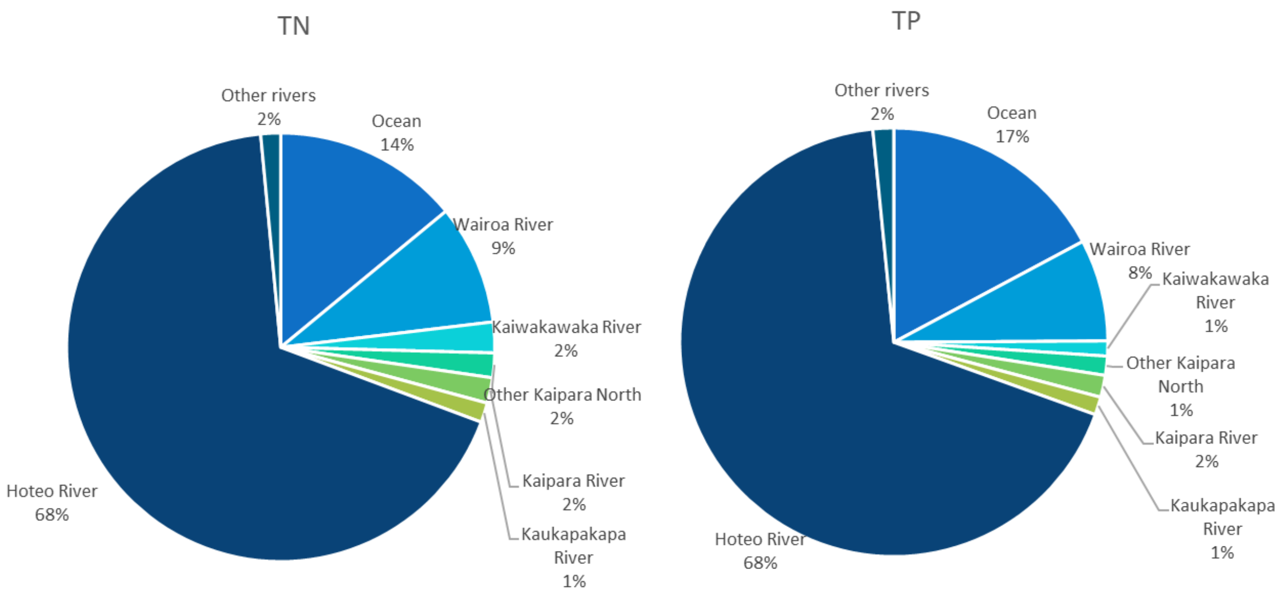

Figure 3-26: Sources of TN and TP in the Hoteo Estuary.

3.7.7 Tauhoa Estuary zone

The Tauhoa Estuary zone extends inland of a line between Karaka Point and Breach Point. The main inflow in this zone is the Whanaki River, which contributes 3% of TN and 2% of TP. The Wairoa River is the largest riverine source of TN and TP (16% and 14% respectively). Similar amounts of TN originate from rivers in the northern and central parts of Kaipara Harbour (28%) as from the southern part (27%), while the ocean is the single largest source of both TN (45%) and TP (54%).

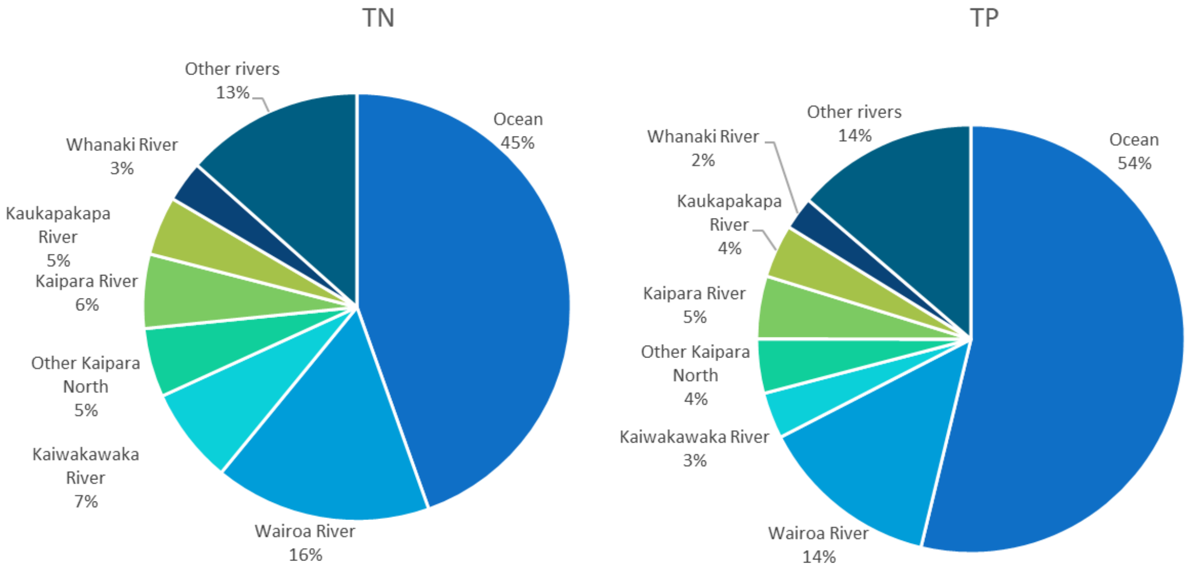

Figure 3-27: Sources of TN and TP in the Tauhoa Estuary.

3.8 Waitematā Harbour and Tāmaki Estuary nutrient model results

3.8.1 Predicted TN and TP distributions in Waitematā Harbour and Tāmaki Estuary

Figure 3-28 and Figure 3-29 show the modelled distributions of TN and TP in the Waitematā Harbour and Tāmaki Estuary. In both estuaries, TN and TP are highest in the headwaters, decreasing towards the estuary mouths. TN concentrations are highest near Rangitopuni.

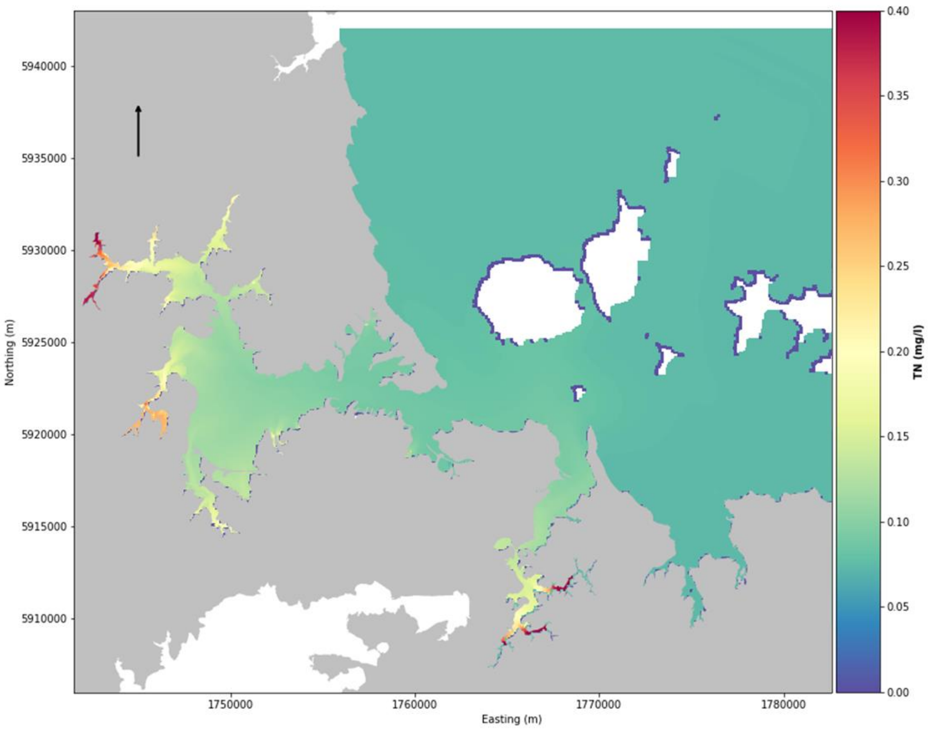

Figure 3-28: Distribution of potential Total Nitrogen (TN) in the Waitematā Harbour and Tāmaki Estuary. Colours show the modelled TN concentrations averaged over a spring-neap period for median stream flows and concentrations.

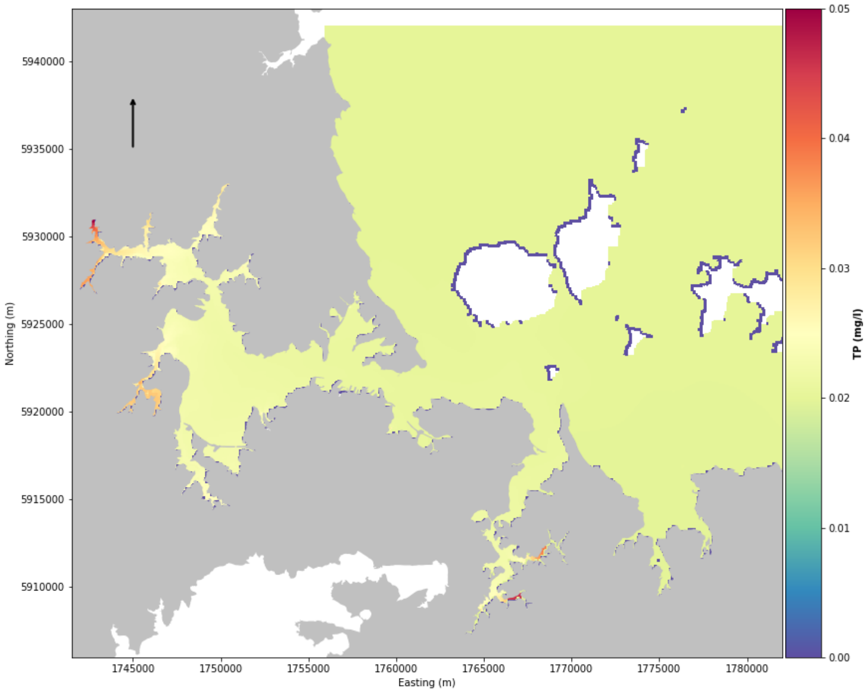

Figure 3-29: Distribution of potential Total Phosphorus (TP) in the Waitematā Harbour and Tāmaki Estuary. The colours show the modelled TP concentrations averaged over a spring-neap period for median stream flows and concentrations.

The estuary zones and locations of the largest inputs of TN to the Waitematā Harbour and Tāmaki Estuary are shown in Figure 3-30 and Figure 3-31, respectively. The estuary subzone for the Upper Waitematā is the harbour north of Scotts Point but excluding the subzones for the Waiarohia Inlet, Rawawaru Creek, Brigham Creek, Rangitopuni Creek, Paremoremo Creek, Lucas Creek and Hellyers Creek. The Central Waitematā subzone is the harbour south of Scotts Point and west of O'Niells Point, excluding the Inner Waitematā, Hendersons Creek and Whau Estuary subzones.

In the Waitematā, the largest sources of TN are Rangitopuni Creek and Brigham Creek, with Momutu Stream, Hendersons Creek and Lucas Creek also significant sources. Otara Creek is the largest input of TN to the Tāmaki Estuary.

Figure 3-30: Locations of the terminal reaches of rivers and streams that discharge to the Waitematā Harbour. Filled points are the streams included in this study, and account for 90% of the inflow to the estuary. These points are coloured by TN load from white to red, with increasing redness indicating increasing loads. Names of streams, where known, are given in white text. The yellow polygons circle each of the estuary subzones (names of zones given in yellow text) for which time- and spatially averaged nutrient concentrations have been calculated. Zones are also defined for the Upper Waitematā (blue) and Central Waitematā (green) which exclude other subzones.

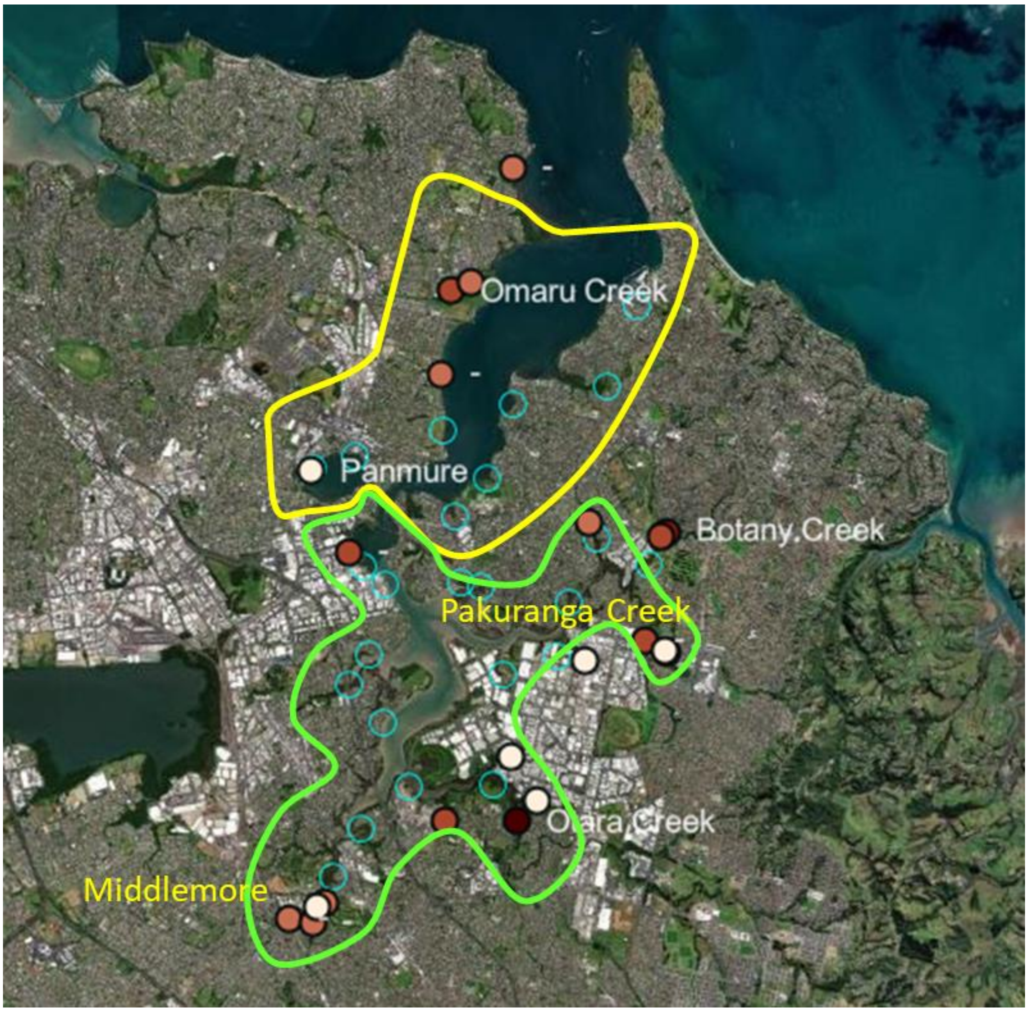

Figure 3-31: Locations of terminal reaches of rivers and streams that discharge to the Tāmaki Estuary. Filled points are the streams included in this study, and account for 90% of the inflow to the estuary. These points are coloured by TN load from white to red, with increasing redness indicating increasing loads. Open blue circles show other terminal reaches not included in this study. The Lower Tāmaki zone is outlined in yellow, and the Upper Tāmaki zone in green. Other areas referred to are noted in yellow. Note that names could not be found for most of the streams.

Modelled TN and TP concentrations within the different zones of the Waitematā Harbour are shown in Figure 3-32. TN concentrations are highest in Brigham Creek and Rangitopuni Creek (> 0.300 mg/L) and lowest in Hobson Bay (< 0.100 mg/L). TP concentrations are low throughout the estuary.

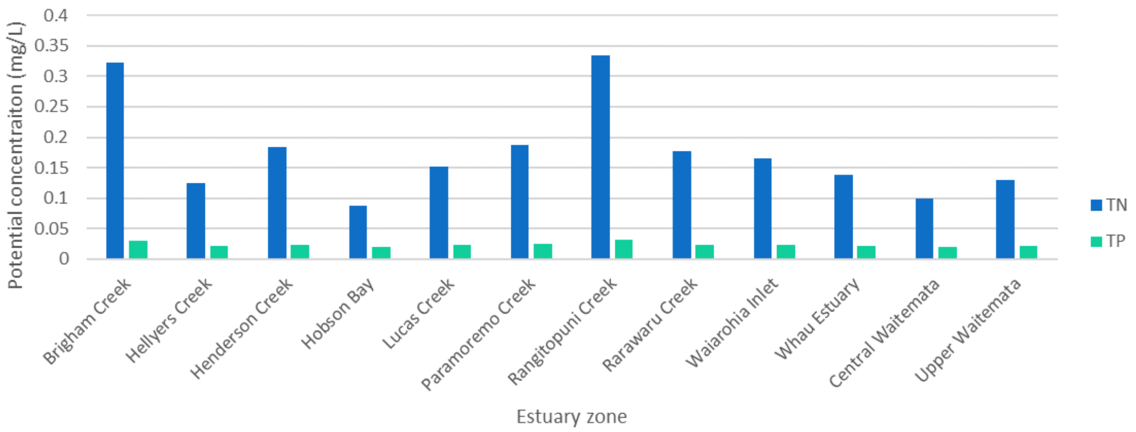

Figure 3-32: Time and spatially averaged TN and TP concentrations in zones of Waitematā Harbour. See Figure 3-30 for the boundaries of estuary subzones.

Only two zones were considered for the Tāmaki Estuary. TN concentrations are higher (~0.380 mg/L) in the upper estuary compared to the lower estuary (~0.110 mg/L) which is more ocean dominated Figure 3-33. Average TP is low (0.020–0.030 mg/L) in both parts of the estuary.

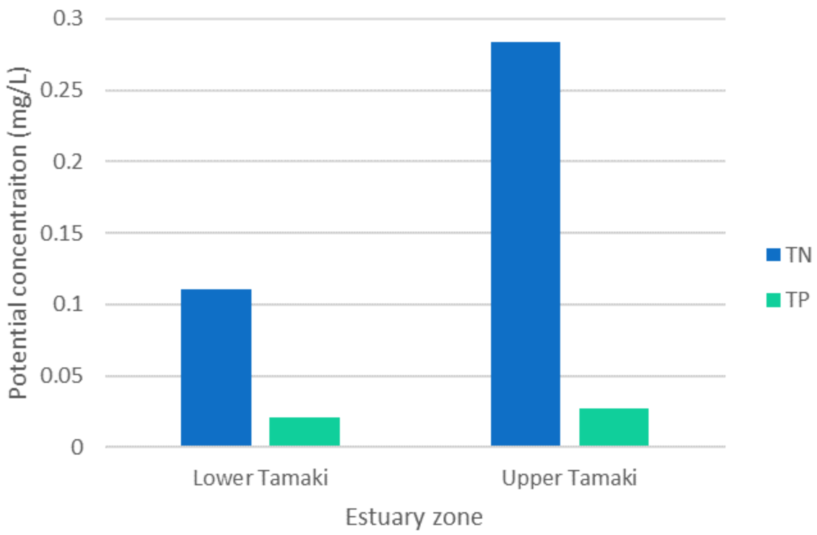

Figure 3-33: TN and TP concentrations in the Tāmaki Estuary. See Figure 3-31 for the boundaries of estuary subzones.

3.8.2 Comparison to observed nutrient concentrations

Locations and site numbers of water quality monitoring sites in the Waitematā Harbour and Tāmaki Estuary are shown in Figure 3-34, and mean observed TN and TP concentrations compared to those predicted by the model in Figure 3-35.

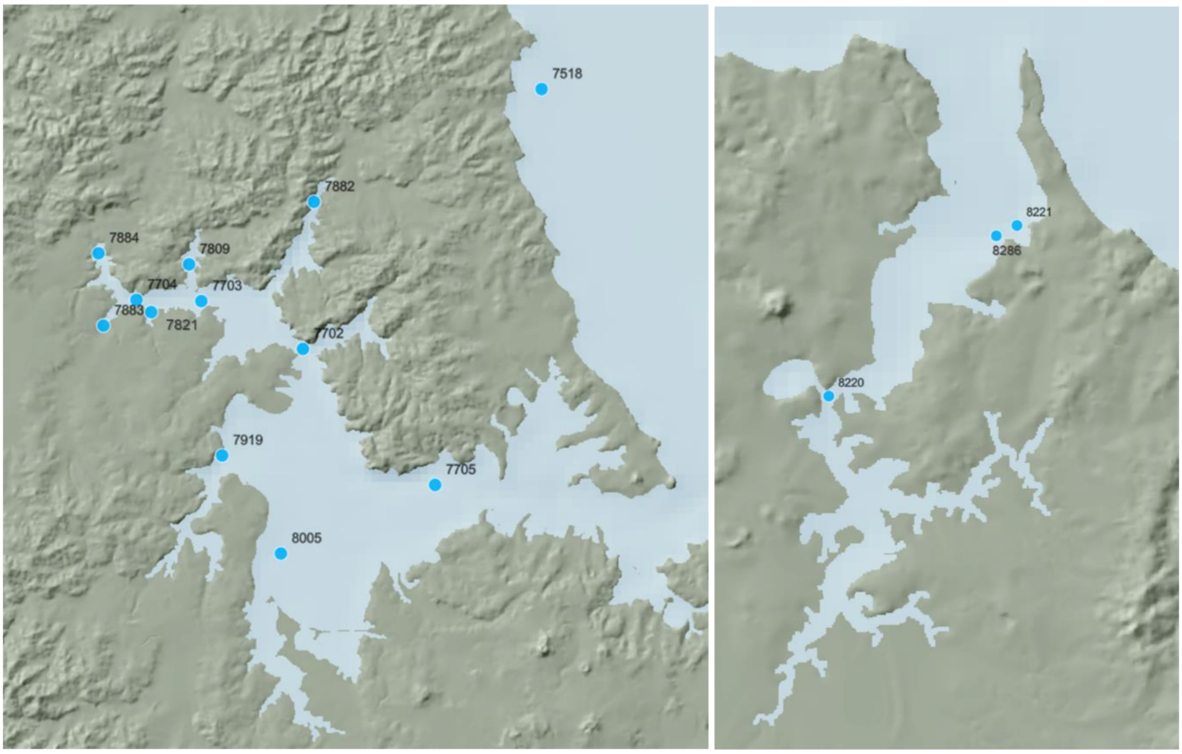

Figure 3-34: Monitoring sites in Waitematā Harbour (left) and Tāmaki Estuary (right). Mean values of total nitrogen (TN) and total phosphorus (TP) were calculated for each site from data across the entire available date range, and also from data collected between 01/01/2013 and 01/01/2018.

The model tends slightly overestimate TN in the Waitematā Harbour, and underestimate in the Tāmaki Estuary. TP is consistently underestimated across all sites in both estuaries. However, the model does consistently indicate the relative magnitude of both nutrients between sites.

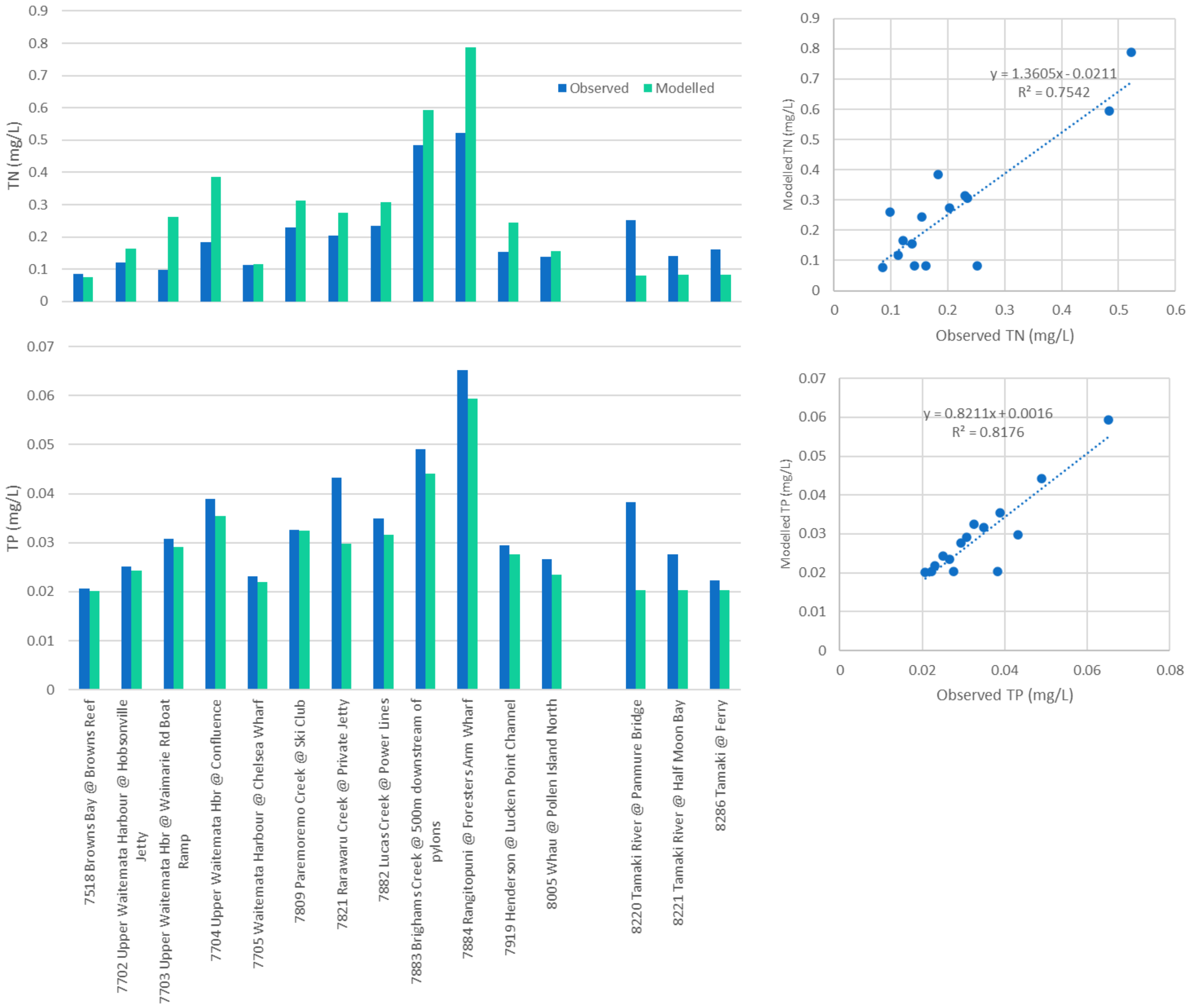

Figure 3-35: Comparison between observed and modelled TN and TP concentrations in the Waitematā Harbour and Tāmaki Estuary. Shown are comparisons between modelled values and mean measured TN and TP values calculated for each site from the entire available data record.

3.8.3 Upper Waitematā

The ocean provides just over half of the TN, and most (84%) of the TP, in the Upper Waitematā (the region north of Scotts Point, excluding the other subzones in the upper reaches of the estuary). The biggest riverine source of TN is Rangitopuni Creek (17%), followed by Brigham Creek (12%). Other streams in the upper Waitematā (including Lucas Creek, Hellyers Creek, Paremoremo Creek and Rarawaru Creek) contribute 4% of TN. Hendersons Creek, which is in the central Waitematā, contributes 7% of TN, similar to the total from all other streams in the central or lower Waitematā.

The relative order of the size of inputs of TP from the various streams are similar to TN, with Rangitopuni Creek, Brigham Creek and Henderson Creek being the largest riverine sources of TP.

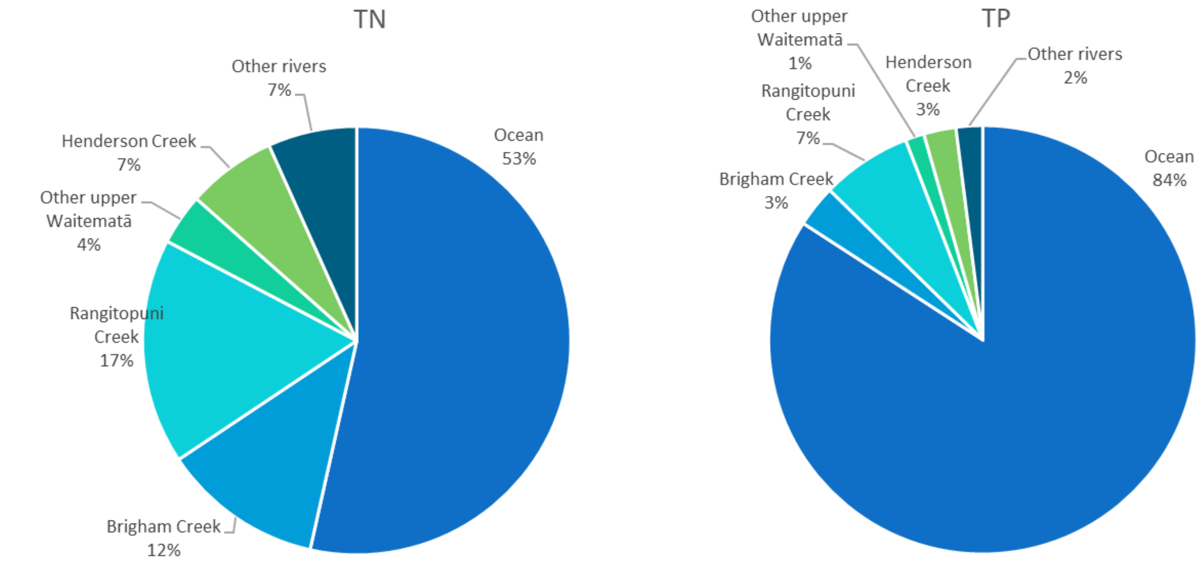

Figure 3-36: Sources of TN and TP in the Upper Waitematā.

3.8.4 Central Waitematā

The Central Waitematā region of the harbour (south of Scotts Point, west of O'Niells Point excluding Hendersons Creek and Whau Estuary) is ocean dominated with nearly three quarters (73%) of TN and 93% of TP coming from coastal waters. Most of the riverine sourced TN (17% of the total) comes from the inner part of the harbour, particularly Rangitopuni Creek (7%) and Brigham Creek (5%). Hendersons Creek contributes 6% of TN, and all other streams contribute a further 4% with about half of that coming from the Whau Estuary subzone.

Riverine sources account for only ~7% of the TP in the Central Waitematā, with most of that (~4%) coming from streams in the inner harbour, particularly Rangitopuni Creek and Brigham Creek.

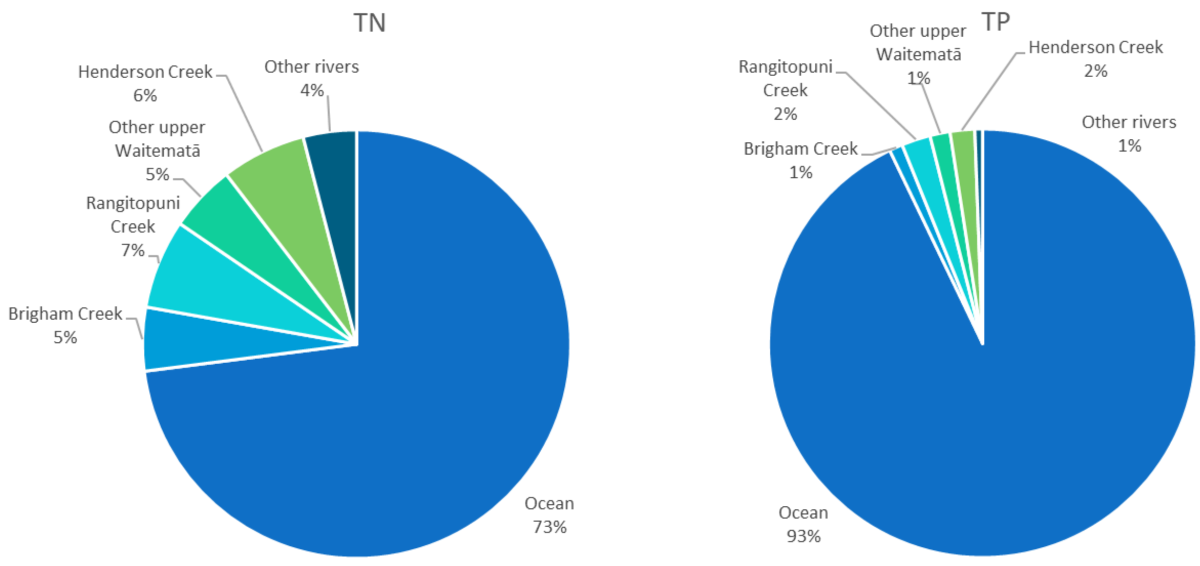

Figure 3-37: Sources of TN and TP in the Central Waitematā.

3.8.5 Brigham Creek zone

Brigham Creek is the largest source of TN (47%) in the Brigham Creek zone. The second largest source of nutrient is Rangitopuni Creek, contributing 28% of TN, while all other streams in the Waitematā Harbour are responsible for 7% of TN in this part of the estuary.

The ocean provides about half (52%) of TP, with Brigham Creek (23%) and Rangitopuni Creek (20%) responsible for most of the remainder.

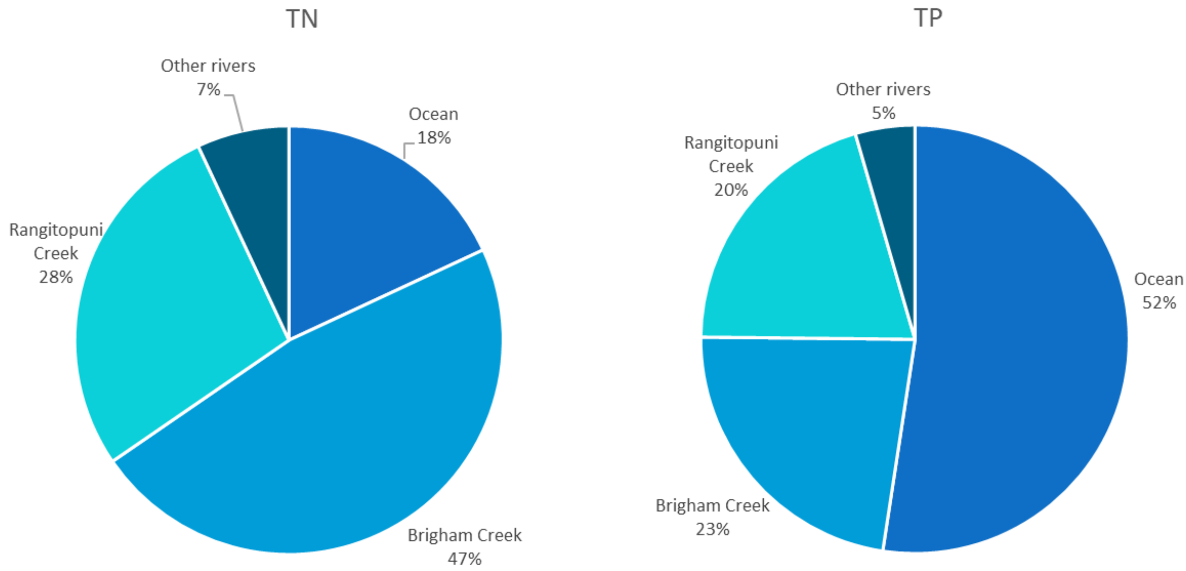

Figure 3-38: Sources of TN and TP in Brigham Creek.

3.8.6 Hellyers Creek zone

Streams within the Hellyers Creek zone account for only a small portion of TN and TP within this zone (7% TN and 5% TP). The ocean is the largest source of both TN and TP to Hellyers Creek. The largest freshwater nutrient source is Rangitopuni Creek, which contributes 14% of TN and 5% of TP. Brigham Creek is the next largest source of TN (10%) and TP (3%). Streams in the Henderson Creek area (particularly Hendersons Creek and Momutu Stream) contribute a further 7% of TN and 3% of TP, while the remainder comes from other inflows to the Waitematā Harbour, with Lucas Creek (3% of TN, 1% of TP) and Waiarohia Stream (2% of TN, <1% of TP) being the biggest contributors.

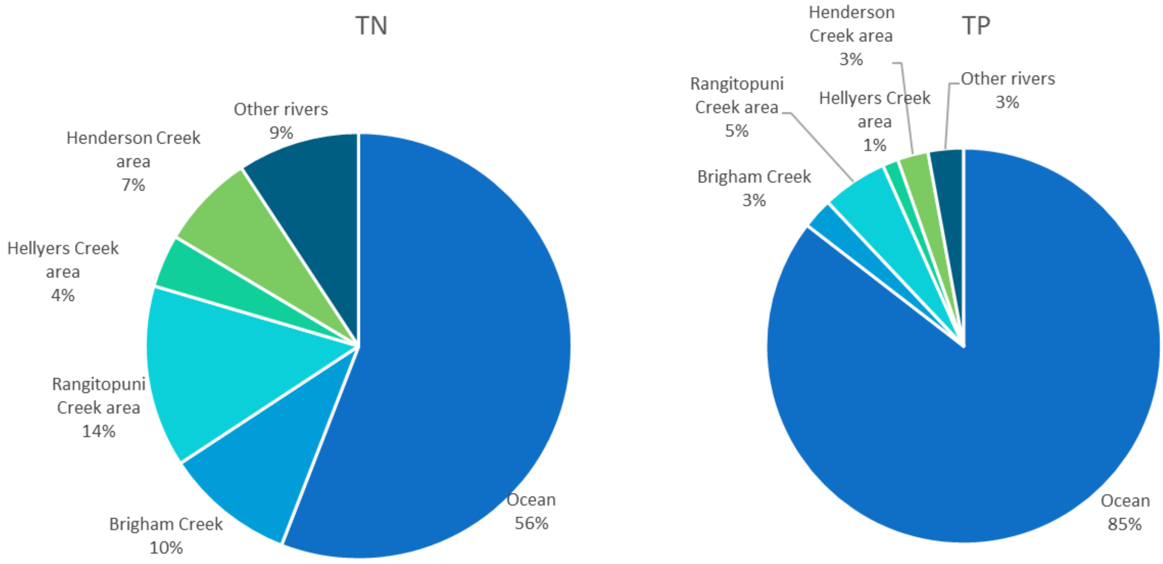

Figure 3-39: Sources of TN and TP in Hellyers Creek.

3.8.7 Henderson Creek zone

The majority of TN (57%) in the Henderson Creek zone comes from local streams discharging into this part of the estuary. It was necessary to apply the same tracer to several streams within this part of the estuary, so it is not possible to accurately apportion nutrients between Henderson Creek, Momutu Stream, Rawawaru Stream, Lincoln Stream and Makomako Stream. However, 53% of the total TN load from these five streams comes from Henderson Creek and a further 38% from Momutu Stream, so we infer that these are the dominant TN (and TP) sources. Brigham Creek and the streams in the Rangitopui Creek area collectively contribute a further 8% of TN and 8% TP. The ocean supplies around 31% of TN.

TP originates mostly from the ocean (67%), with 28% coming from streams in the Henderson Creek area.

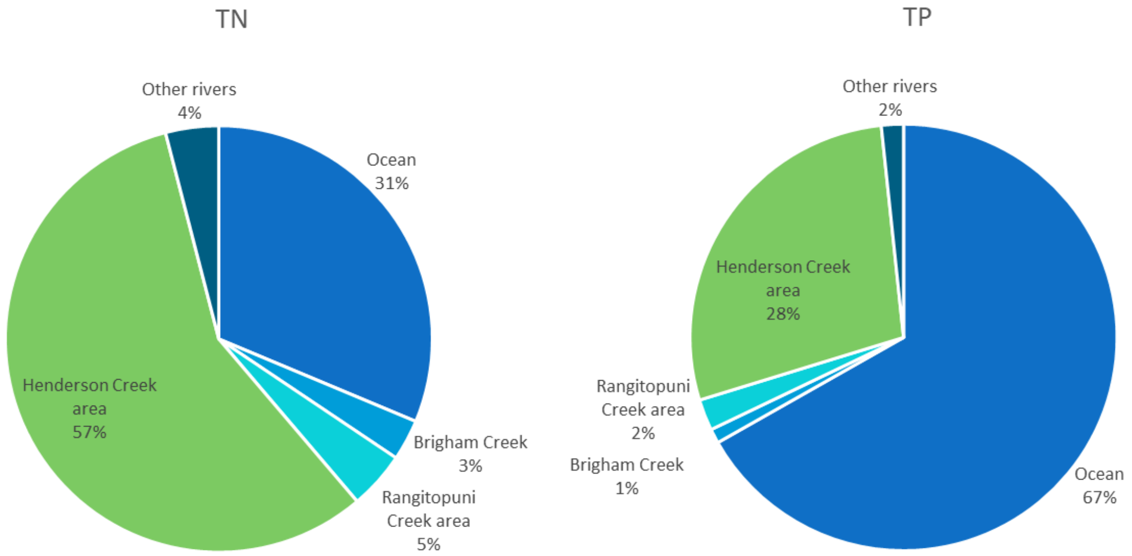

Figure 3-40: Sources of TN and TP to the Hendersons Creek zone of Waitematā Harbour.

3.8.8 Hobson Bay

Hobson Bay is an ocean-dominated part of the harbour, with most of the TN (85%) and TP (97%) coming from the ocean. The local streams within Hobson Bay contribute only a small portion of TN (2%) and TP (<1%), with the Rangitopuni Creek area, Henderson Creek area and Brigham Creek each responsible for a similar portion of the nutrient concentration.

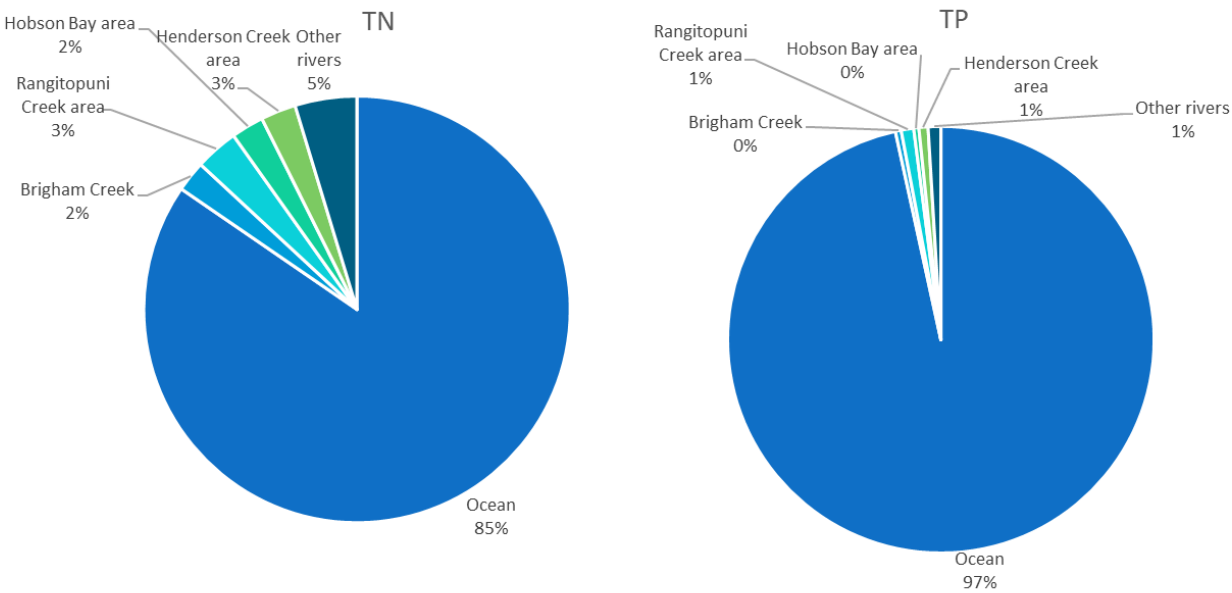

Figure 3-41: Sources of TN and TP to Hobson Bay, Waitematā Harbour.

3.8.9 Lucas Creek

The modelling indicates that the largest riverine source of TN and TP to the Lucas Creek area are streams in the Rangitopuni Creek area (18% TN, 8% TP). Brigham Creek provides a similar amount of

TN (12%) and slightly less TP (4%) that what comes from Lucas Creek itself (12% TN, 6% TP). Streams in the Henderson Creek area provide a similar amount of TN and TP to all other rivers in the harbour (excluding those already mentioned).

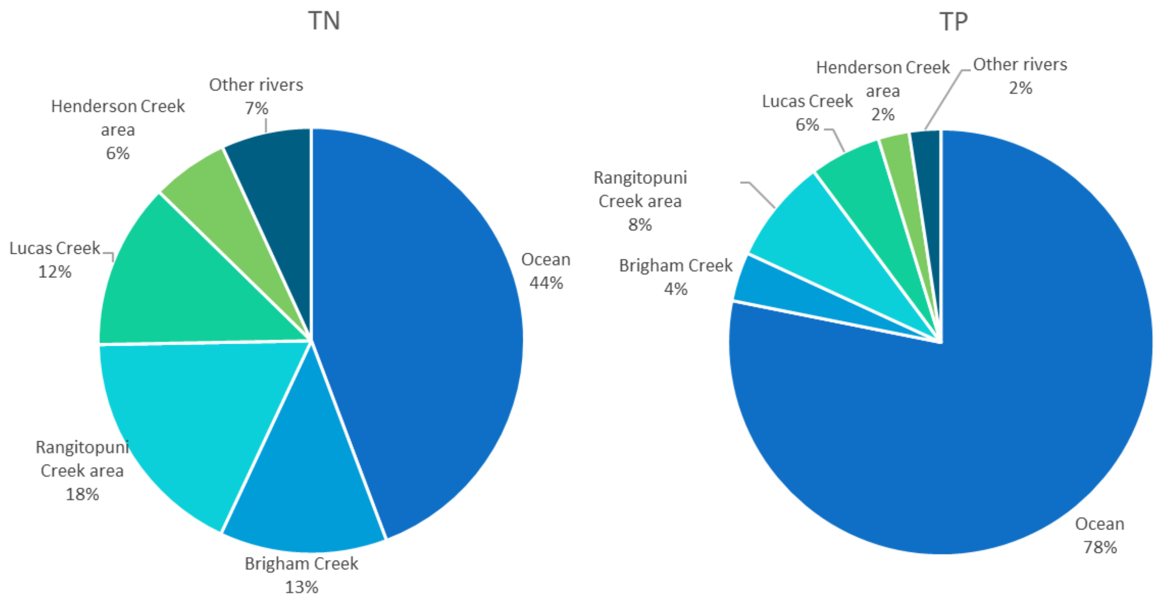

Figure 3-42: Sources of TN and TP to the Lucas Creek area, Waitematā Harbour.

3.8.10 Paremoremo Creek zone

Paremoremo Creek is a relatively minor source of TN (13%) and TP (7%) to the Paremoremo Creek zone. Most of the TN in this part of the harbour comes from the ocean (35%), Rangitopuni Creek area (24%) and Brigham Creek (17% TN), both of which are further towards the headwaters of the estuary. The ocean provides most of the TP (70%). Similarly to TN, the dominant riverine source is the Rangitopuni Creek area (12%). Similar amounts of TP originate from Pareomoremo Creek (7%) as from Brigham Creek (6%).

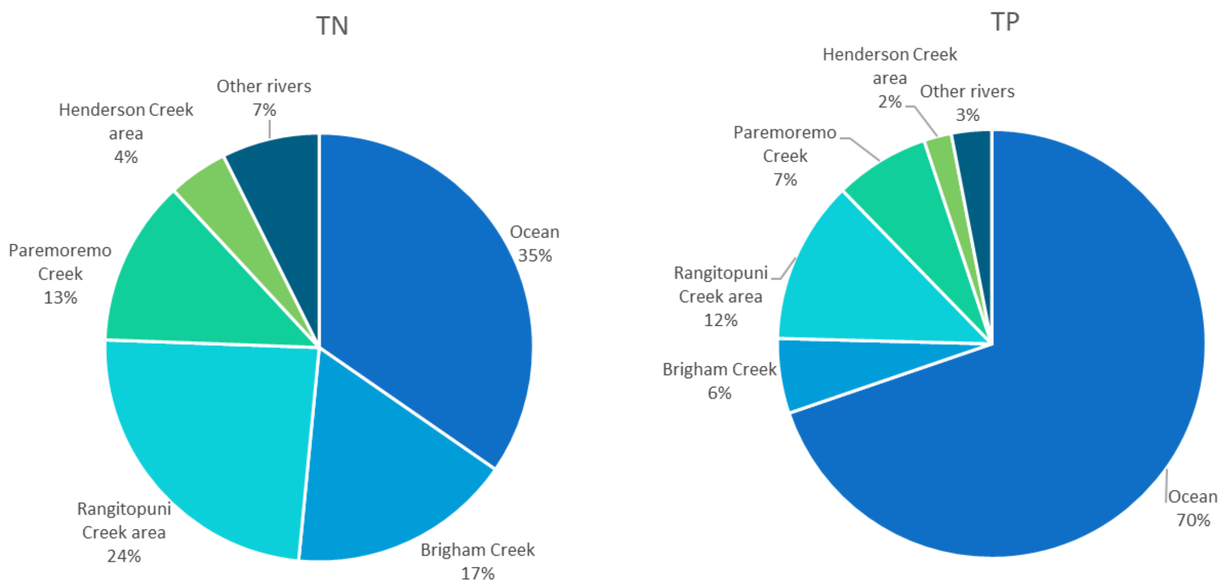

Figure 3-43: Sources of TN and TP in the Paremoremo Creek zone of Waitematā Harbour.

3.8.11 Rangitopuni Creek zone

The Rangitopuni Creek zone has the highest TN and TP concentrations of all estuary zones (Figure 3-32). The largest source of TN and TP are the inflows within the Rangitopunui Creek zone (64% TN, 47% TP), most of which comes from Rangitopunui Stream (the other unnamed stream having only small influence). The nearby Brigham Creek is a significant source of TN (15%) and TP (7%).

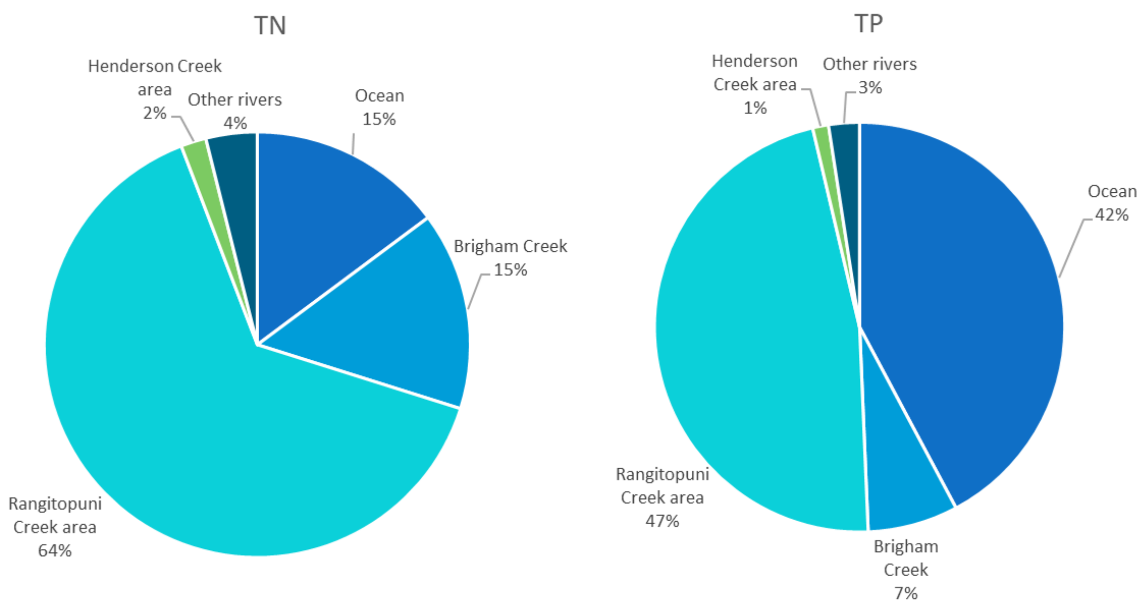

Figure 3-44: Sources of TN and TP to the Rangitopuni Creek zone, Waitematā Harbour.

3.8.12 Rarawaru Creek zone

Like other parts of the inner north-west of Waitematā Harbour, concentrations are strongly influenced by TN coming from Brigham Creek (20%) and Rangitopuni Stream (28%). The same two streams are the dominant riverine sources of TP (7% and 14%, respectively), but the ocean is the largest TP source (73%) in this zone. Rawarawaru Creek has very minor influence on TN and TP concentrations, being responsible for only ~1% of TN and TP within this part of the harbour.

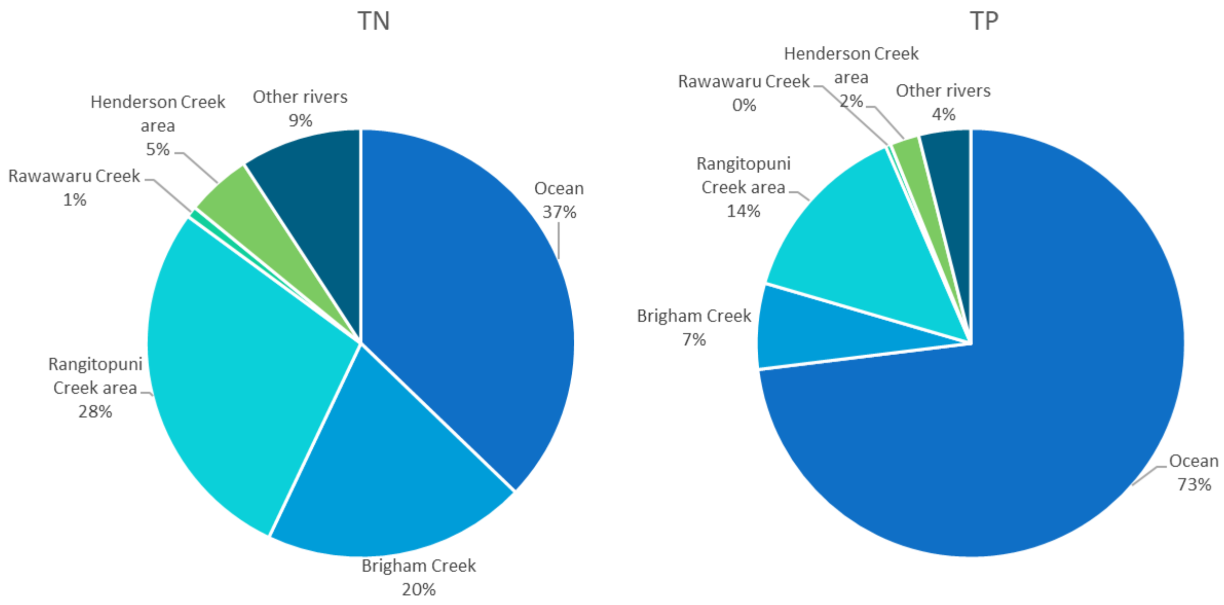

Figure 3-45: Sources of TN and TP to the Rarawaru Creek zone, Waitematā Harbour.

3.8.13 Waiarohia Inlet zone

Waiarohia Stream is the single largest non-oceanic source of TN (22%) to Waiarohia Inlet. The other main sources of TN are Rangitopuni Stream and Brigham Creek.

The ocean provides three quarters (78%) of TP, with Waiarohia Stream itself providing about 8%. Collectively, Rangitopuni Stream and Brigham Creek a further 9% of TP, with the rest coming from elsewhere in the harbour.

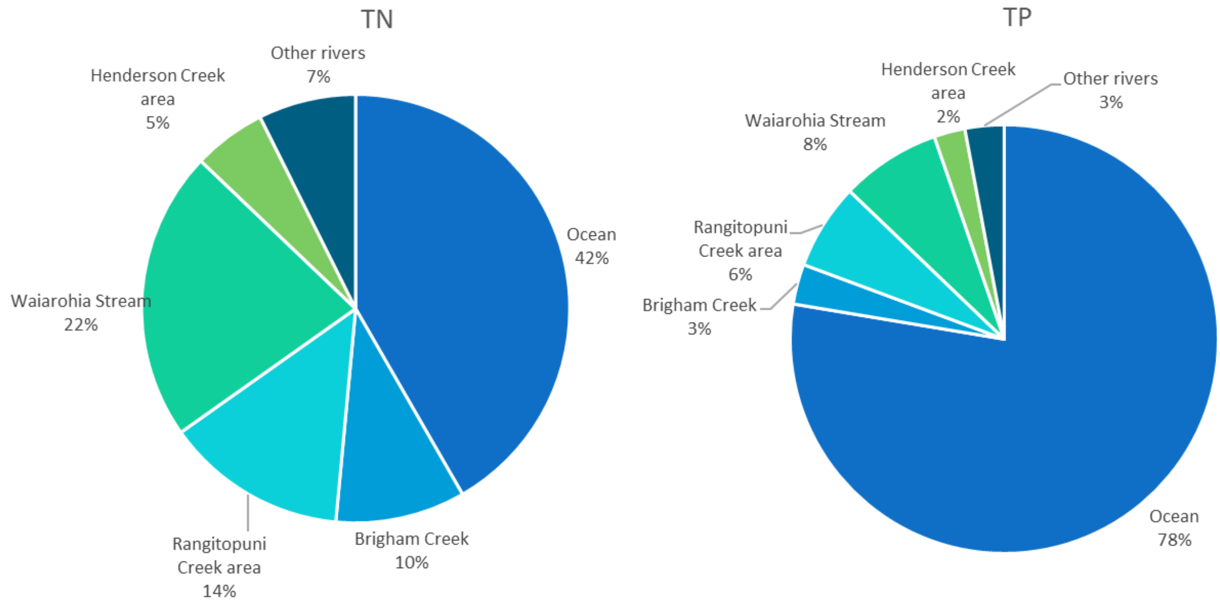

Figure 3-46: Sources of TN and TP to the Waiarohia Inlet zone, Waitematā Harbour.

3.8.14 Whau Estuary zone

Half of the TN (50%) and most of the TP (84%) in the Whau Estuary comes from the ocean. The main riverine sources are from the streams that discharge directly into this sub-estuary. Avondale Stream and Taroa Stream contribute 23% of TN, with another 5% coming from Wairau Creek.

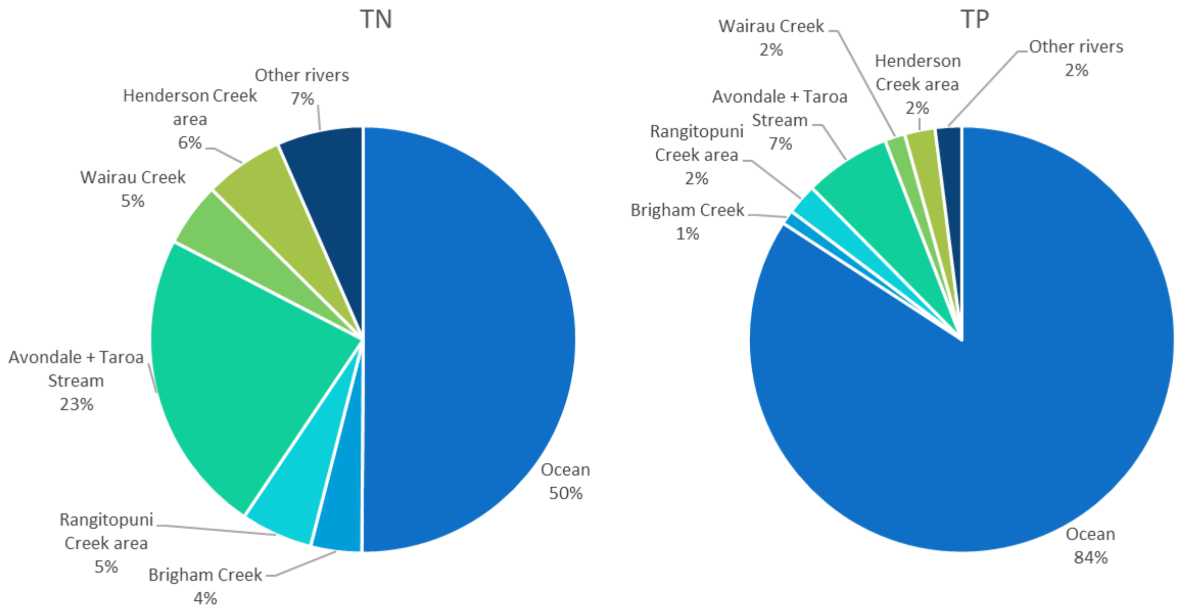

Figure 3-47: Sources of TN and TP to Whau Estuary in the Waitematā Harbour.

3.8.15 Upper Tāmaki

Otara Creek is the largest source of TN (48%) and the largest non-oceanic source of TP (30%) to the Upper Tāmaki. The second largest riverine sources of TN and TP are the streams in the

Botany/Pakuranga Creek reach of the estuary, and Botany Creek contributes 44% of the TN load within that reach.

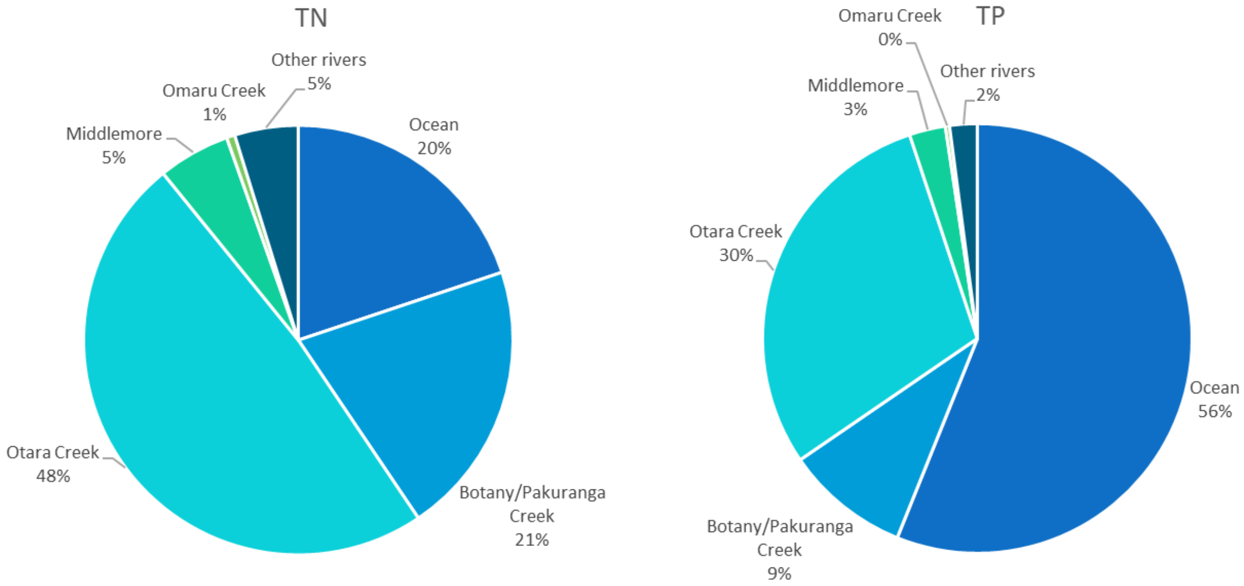

Figure 3-48: Sources of TN and TP in the Upper Tāmaki Estuary.

3.8.16 Lower Tāmaki

In the Lower Tāmaki, most of the TN (65%) and nearly all of TP (91%) comes from the ocean. Of the riverine sources, most of TN and TP comes from streams in the upper estuary, particularly from Botany/Pakuranga Creek, Otara Creek, and from around Middlemore. Less than 10% TN and ~2% TP comes from streams in the lower estuary.

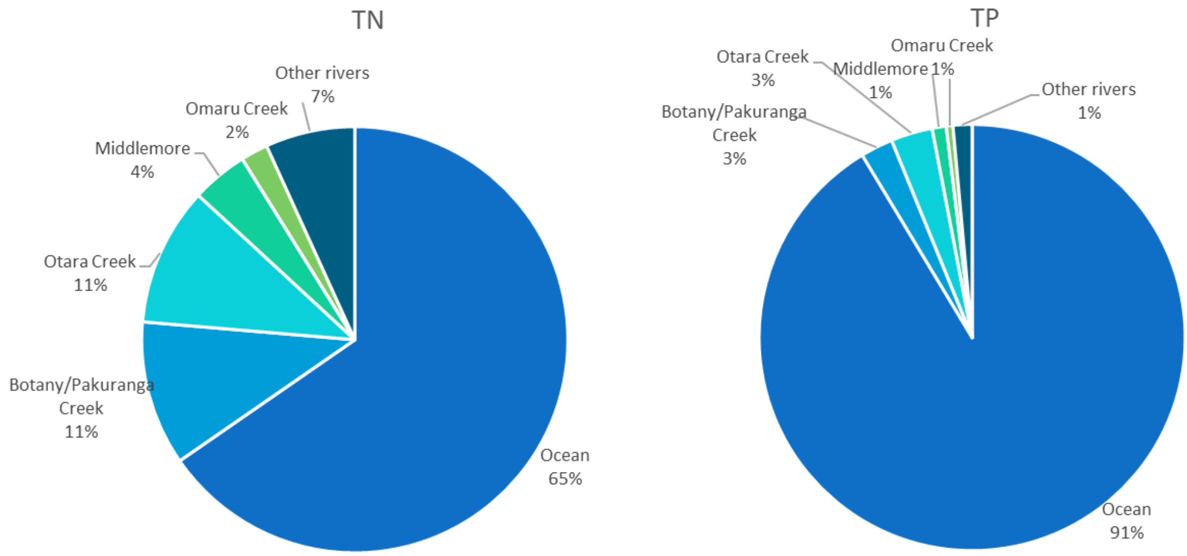

Figure 3-49: Sources of TN and TP in the Lower Tamaki Estuary.

4 Conclusions and recommendations

4.1 Nutrient modelling methods

A goal of this study was to assess the baseline state (defined as state in September 2017) and current state of nutrient loads delivered to estuaries and sub-estuaries in the Auckland region. Comparison of modelled and measured nutrient concentrations across Auckland's larger estuaries showed that we were able to estimate the spatial distributions of TN well. This is important because results also suggest that nitrogen is the nutrient that most limits eutrophication in all estuaries in the region. Estimates for TP were less accurate, potentially reflecting the accuracy with which we can estimate loads of TP from rivers. The method we employed for small estuaries is also proven to work well to estimate the risk of eutrophication via TN loading to estuaries (Plew, Zeldis et al. 2020), albeit with data derived largely from southern New Zealand. Comparison of single 'box' model estimates of nutrient concentrations to nutrient estimates from hydrodynamic models made it clear that the single box models give a relatively poor estimates of nutrient conditions in Auckland's major estuaries. In particular, hydrodynamic models highlighted the localised impacts of riverine inputs from some catchments on the estuary arms they flow to. These hydrodynamic models now provide an appropriate method to assess the likely effects of changes in nutrient loads to these larger estuaries, by applying altered tracer concentrations from terminal reaches to the models.

A limitation of the methods of assessing nutrient concentrations and eutrophication risk in this study is that they use 'steady-state' nutrient load estimates. We were not able to calculate differences between baseline and current state using these steady state estimates. This may be important because:

1. Loads at SoE sites upstream of the estuaries differ between years, e.g., between the years 2013–2017 and the full data record shown in Table 3-6.
2. Timing of contaminant (e.g., sediment and nutrient) loading to estuaries may alter effects on estuary attributes.
3. Management of nutrient loads to estuaries requires understanding of how land use change results in changes to loads.

Auckland Council's Freshwater Management Tool (FWMT) would appear a suitable tool for estimating changes in nutrient load through time. This work highlighted issues with its application to estuary management in its current state. We would therefore recommend that work is undertaken to check the catchments represented by FWMT nodes on the coastal boundary against the full upstream catchment of coastal 'pour points' (modelled terminal reaches). We observed during our work that the FWMT coastal pour points do not cover many of the known rivers and streams entering estuaries in the Auckland region. We would also recommend remedying this as a priority for research to enable the use of FWMT as a management tool for estuaries.

4.2 Water quality and flow monitoring sites

With regard to recommendations for monitoring sites, Auckland's estuaries have one of the best and long-standing monitoring networks in New Zealand. However, if new monitoring sites are installed, we would recommend that these are placed to monitor contaminant concentration and flow rates at terminal river reaches flowing to estuaries. This would allow comparison of time-varying modelled loads (e.g., from the FWMT) against measurements. These comparisons could provide the basis for any subsequent model calibration or other adjustments, such as adjusting steady-state loads at terminal reaches to different time-periods of interest. We recommend that rivers that contribute larger loads of nutrients to estuaries – particularly those estuaries at risk of eutrophication – should be considered for terminal reach monitoring.

Terminal reach monitoring may also aid modelling of TP concentrations in estuaries. In this work, TP concentrations measured in estuaries did not match model predictions as well as did TN concentrations. Terminal reach TP loads may be more difficult to model than TN loads and terminal reach monitoring may shed light on this issue.

A further point regarding monitoring is that the mixing models used in our work are highly reliant on the accuracy of the TN and TP concentration of 'oceanic' coastal water (coastal water largely unaffected by riverine runoff). We suggest that maintaining a good understanding of nutrient concentrations in this oceanic coastal water should be a continuing priority for monitoring.

4.3 Ecological monitoring and modelling

This work provided predicted ecological state in Auckland estuaries under current nutrient loads (Table 3-7 and Table 3-8) and nutrient loads corresponding to thresholds between bands of eutrophication susceptibility (Table 3-9). However, we note that the relationships between loads and ecological responses used to make these predictions came mostly from estuaries in the South Island of New Zealand. It is highly likely that differences between biota (e.g., mangroves, which alter benthic conditions for algal growth), climate, and coastal water chemistry will alter these load-to-response relationships. For example, recent work in Canterbury has highlighted interactions between nutrient additions to estuaries and oceanic heatwaves in controlling algal growth in estuaries (Gadd, Dudley et al. 2020; Tait, Zeldis et al. 2022). For these reasons, we recommend that the estimates from tables 3-7 to 3-9 are used as guides for regional quantification of relationships between loads and responses of estuary attributes. These tables provide information on the ranges of potential nutrient concentrations and eutrophication susceptibilities present across Auckland estuaries. As such, they can guide which estuaries to include in monitoring of estuary attributes to generate predictive relationships between loading and attribute responses in northern New Zealand. This regional quantification is vital to assess the ecological consequences to estuaries and sub-estuaries in the Auckland region resulting from changes in nutrient concentrations, and whether proposed nutrient targets in streams and rivers will safeguard against eutrophication in receiving estuaries.

It is notable that eutrophication risk for Auckland estuaries is generally low relative to estuaries nationally (Plew, Zeldis et al. 2020), and also within northern New Zealand (Dudley, Milne et al. 2022). This means that predictive relationships between loading and attribute responses generated from estuaries only in the Auckland region are unlikely to accurately represent attribute responses under very high nutrient loading rates. While estuaries under high levels of eutrophication may come with significant cost to ecosystem services (Fulford, Russell et al. 2020) they also provide information to scientists and managers on the potential results of eutrophication elsewhere. For example, the New River Estuary and Avon Heathcote Estuary provide understanding of eutrophication responses under high nutrient loads in southern New Zealand (Barr, Zeldis et al. 2020; Zeldis, Depree et al. 2020; Stevens, Forrest et al. 2022). These estuaries fill a useful place at the top end of regression relationships used to set thresholds for nutrient loads in the ETI (Plew, Zeldis et al. 2020). For this reason, we recommend that Auckland Council scientists consider collaboration with other northern councils when developing relationships between loading and attribute responses for northern estuaries, including those in the Auckland / Tāmaki Makaurau region. For example, the review of

Dudley, Milne et al. (2022) includes ETI Tool 1 assessments that show several estuaries present in the Northland region with high susceptibility to eutrophication at current nutrient loads. Including these estuaries in a regional attribute monitoring programme could provide important information on the implications of <u>increases</u> in nutrient loading in Auckland estuaries.

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Appendix A Estuary properties

Table A-1: Estuary properties as used in this study. New Zealand Coastal Hydrosystem (NZCHS) names from Hume, Gerbeaux et al. (2016).

Estuary ID	Estuary name	NZCHS type	NZCHS class	ETI class	LAT	LON	Mean freshwater inflow (m^3/s)	Volume at high tide (m^3)	Tidal prism (m^3)	Intertidal area (%)	Estuary area (m^2)	Mean Depth (m)
49	Pakiri River	7A	Tidal lagoon (permanently open)	SSRTRE	-36.2408	174.732	0.752	213063	155329	35.24	89150	2.39
50	Omaha Cove	11	Coastal embayment	DSDE	-36.2934	174.8214	0.069	2256953	624012	0	285067	7.92
51	Whangateau Harbour	7A	Tidal lagoon (permanently open)	SIDE	-36.3285	174.7933	0.696	11663589	9491105	85.44	7460453	1.56
52	Millon Bay	11	Coastal embayment	DSDE	-36.4	174.7636	0.101	1953712	1714237	61.55	1017808	1.92
53	Matakana River	8	Shallow drowned valley	SIDE	-36.403	174.7429	1.102	4786883	4786883	75.98	4177585	1.15
78	Mahurangi Harbour System	8	Shallow drowned valley	SIDE	-36.5119	174.7325	3.088	67261470	44892812	51.18	24565021	2.74
79	Te Muri-O-Tarariki	7A	Tidal lagoon (permanently open)	SIDE	-36.5173	174.7215	0.105	325814	325629.2	99.93	264554	1.23
80	Puhoi River	7A	Tidal lagoon (permanently open)	SIDE	-36.5325	174.7246	1.104	3693641	2697410	70.58	1693119	2.18
81	Waiwera River	7A	Tidal lagoon (permanently open)	SIDE	-36.5477	174.7167	0.779	2364498	1659432	64.49	992771	2.38
82	Orewa River	7A	Tidal lagoon (permanently open)	SIDE	-36.5945	174.7091	0.450	1899475	1758642	89	1280293	1.48
83	Okoromai Bay	11	Coastal embayment	DSDE	-36.6213	174.8118	0.024	2832822	2310461	27	1059101	2.67
84	Hobbs Bay (Gulf Harbour)	11	Coastal embayment	DSDE	-36.6318	174.7842	0.072	1075639	601266.5	0	237186	4.54
85	Weiti River	6B	Tidal river mouth (spit enclosed)	SIDE	-36.6553	174.7577	0.514	3960748	3960748	63.04	2833304	1.40
86	Okura River	7A	Tidal lagoon (permanently open)	SIDE	-36.6574	174.752	0.301	861712	861712	79.27	1359335	0.63
90	Mangemangeroa Estuary WES	8	Shallow drowned valley	DSDE	-36.9127	174.9563	0.380	920056	920056.5	86.92	602242	1.53
91	Turanga Creek WES	8	Shallow drowned valley	SIDE	-36.9145	174.9616	0.355	2202889	2202889	73.64	1493124	1.48

Estuary ID	Estuary name	NZCHS type	NZCHS class	ETI class	LAT	LON	Mean freshwater inflow (m^3/s)	Volume at high tide (m^3)	Tidal prism (m^3)	Intertidal area (%)	Estuary area (m^2)	Mean Depth (m)
92	Waikopua Creek WES	8	Shallow drowned valley	DSDE	-36.9035	174.9809	0.171	2032921	2032921	99.97	1739241	1.17
93	Wairoa River	8	Shallow drowned valley	SIDE	-36.9377	175.0959	5.027	8679788	5774004	41.96	2503260	3.47
220	Waitakere River (Bethells Beach)	4C	Beach Stream (stream with pond)	SSRTRE	-36.8936	174.4296	1.454	55604.12	51823.98	88.69	33423	1.66
250	North Cove	11	Coastal embayment	DSDE	-36.4117	174.8228	0.019	1561974	1089925	37.32	565385	2.76
251	Bon Accord Harbour	11	Coastal embayment	SIDE	-36.4242	174.8134	0.132	12417347	5424129	19.16	2489135	4.99
252	South Cove Harbour	11	Coastal embayment	DSDE	-36.4443	174.8256	0.017	614853	511870	30.59	250330	2.46
253	Gardiner Gap	11	Coastal embayment	DSDE	-36.7668	174.8893	0.018	539215	539215	59.61	354374	1.52
254	Islington Bay	11	Coastal embayment	DSDE	-36.7974	174.9037	0.018	7859547	4754895	6.94	1787308	4.40
255	Matiatia Bay	11	Coastal embayment	DSDE	-36.7806	174.9833	0.017	1743905	988824	2.86	379270	4.60
256	Owhanake Bay	11	Coastal embayment	DSDE	-36.7694	174.9908	0.007	1417337	746236	2.3	293058	4.84
257	Oneroa Bay	11	Coastal embayment	DSDE	-36.7747	175.0213	0.013	12801343	4000498	0.66	1574017	8.13
258	Mawhitipana Bay	11	Coastal embayment	DSDE	-36.7756	175.0422	0.018	2301964	914388	8.76	375598	6.13
259	Te Matuku Bay	11	Coastal embayment	SIDE	-36.8498	175.1322	0.151	2792307	2792307	75.88	2423205	1.15
260	Awaawaroa Bay	11	Coastal embayment	DSDE	-36.8458	175.1038	0.189	10223362	7014047	28.73	2836091	3.60
261	Rocky Bay	11	Coastal embayment	DSDE	-36.8306	175.0549	0.065	4104300	3000404	30.43	1241262	3.31
262	Putiki Bay	11	Coastal embayment	SIDE	-36.8179	175.025	0.137	9953530	7777440	35.45	3354500	2.97
263	Huruhi Bay	11	Coastal embayment	DSDE	-36.8142	175.0038	0.017	26462932	12139148	11.68	4604301	5.75
264	Tryphena Harbour	11	Coastal embayment	DSDE	-36.3243	175.464	0.308	88523586	13082657	4.12	6425122	13.78
265	Blind Bay	11	Coastal embayment	DSDE	-36.2765	175.4241	0.222	33526268	5838203	5.27	2781170	12.05
266	Whangaparapara Harbour	11	Coastal embayment	DSDE	-36.2599	175.3919	0.189	22180522	3508889	13.79	1737549	12.77
267	Port Fitzroy/Port Abercrombie	9	Deep drowned valley	SIDE	-36.1663	175.3044	0.796	347987612	37816307	3.23	18399744	18.91
268	Katherine Bay	11	Coastal embayment	DSDE	-36.1192	175.3471	0.391	27574481	6762917	3.33	3396260	8.12
269	Rangiwhakaea Bay	11	Coastal embayment	DSDE	-36.0862	175.414	0.170	7420318	1700532	1.61	909460	8.16

Estuary ID	Estuary name	NZCHS type	NZCHS class	ETI class	LAT	LON	Mean freshwater inflow (m^3/s)	Volume at high tide (m^3)	Tidal prism (m^3)	Intertidal area (%)	Estuary area (m^2)	Mean Depth (m)
270	Whangapoua Creek	7A	Tidal lagoon (permanently open)	SIDE	-36.1369	175.4365	0.509	2935405	2767183	93.97	2789750	1.05
271	Awana Bay	4C	Beach Stream (stream with pond)	SSRTRE	-36.2087	175.4913	0.351	179805	116826	0	62979	2.86
272	Kaitoke Creek	4C	Beach Stream (stream with pond)	SIDE	-36.2341	175.4923	0.597	281570	195257	30.51	124208	2.27
87	Waitematā Harbour System	8	Shallow drowned valley	SIDE	-36.8362	174.8238	6.986	341571865	177003695	36.16	79848102	4.28
88	Tāmaki River	8	Shallow drowned valley	SIDE	-36.8421	174.8870	1.102	49163825	37427602	40	16963199	2.90
219	Manukau Harbour System (MHS)	8	Shallow drowned valley	SIDE	-37.0716	174.5029	14.167	2215803524	710146881	61.8	365602613	6.06
221	Kaipara Harbour System	8	Shallow drowned valley	SIDE	-36.4542	174.0883	127.741	3992734683	1615117448	41.92	743061027	5.37

Appendix B ETI Tool 3 indicator node values

Table B-1: ETI Tool 3 indicator band probability distributions. The table gives the probability (in %) that the predicted indicator scores lie within each band (A to D). Bandings are described in Table 2-3.

Estuary	Macroalgae				Phytoplankton				Oxygen				Mud				aRPD				TOC				Seagrass				Macrobenthos				ETI band			
	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D
Pakiri River	86	13	0	0	100	0	0	0	100	0	0	0	9	80	9	2	64	29	7	1	66	31	2	0	80	15	4	1	25	72	2	1	70	30	0	0
Omaha Cove	93	7	0	0	1	60	39	0	0	0	1	98	90	9	1	0	74	23	3	0	85	14	0	0	96	2	1	1	47	51	1	1	24	73	3	0
Whangateau Harbour	74	25	1	0	0	0	14	86	100	0	0	0	90	9	1	0	68	27	5	0	82	17	1	0	95	3	1	1	47	51	1	1	71	29	1	0
Millon Bay	93	7	0	0	48	44	8	0	100	0	0	0	90	9	1	0	74	23	3	0	85	14	0	0	96	2	1	1	47	51	1	1	85	15	0	0
Matakana River	86	14	0	0	40	47	13	0	100	0	0	0	90	9	1	0	71	24	4	0	84	15	0	0	96	2	1	1	47	51	1	1	80	20	0	0
Mahurangi Harbour System	97	3	0	0	60	40	0	0	100	0	0	0	90	9	1	0	75	22	3	0	86	14	0	0	96	2	1	1	47	51	1	1	87	13	0	0
Te Muri-O-Tarariki	74	25	1	0	24	16	10	50	100	0	0	0	90	9	1	0	68	27	5	0	82	17	1	0	95	3	1	1	47	51	1	1	72	28	1	0
Puhoi River	74	25	1	0	0	2	98	0	100	0	0	0	90	9	1	0	68	27	5	0	82	17	1	0	95	3	1	1	47	51	1	1	72	28	0	0
Waiwera River	51	44	5	0	0	0	34	66	100	0	0	0	90	9	1	0	60	31	8	1	78	21	1	0	92	5	1	1	46	52	1	1	56	42	2	0
Orewa River	74	25	1	0	30	23	20	27	100	0	0	0	90	9	1	0	68	27	5	0	82	17	1	0	95	3	1	1	47	51	1	1	72	27	0	0
Okoromai Bay	97	3	0	0	60	40	0	0	100	0	0	0	90	9	1	0	75	22	3	0	86	14	0	0	96	2	1	1	47	51	1	1	63	37	0	0
Hobbs Bay (Gulf Harbour)	97	3	0	0	60	40	0	0	100	0	0	0	90	9	1	0	75	22	3	0	86	14	0	0	96	2	1	1	47	51	1	1	68	32	0	0
Weiti River	97	3	0	0	48	44	8	0	100	0	0	0	90	9	1	0	75	22	3	0	86	14	0	0	96	2	1	1	47	51	1	1	90	10	0	0
Okura River	74	25	1	0	30	23	20	27	100	0	0	0	90	9	1	0	68	27	5	0	82	17	1	0	95	3	1	1	47	51	1	1	72	27	0	0
Mangemangeroa Estuary WES	93	7	0	0	95	5	0	0	100	0	0	0	90	9	1	0	74	23	3	0	85	14	0	0	96	2	1	1	47	51	1	1	85	15	0	0
Turanga Creek WES	74	25	1	0	24	16	10	50	100	0	0	0	90	9	1	0	68	27	5	0	82	17	1	0	95	3	1	1	47	51	1	1	72	28	1	0
Waikopua Creek WES	86	14	0	0	31	28	19	21	100	0	0	0	90	9	1	0	71	24	4	0	84	15	0	0	96	2	1	1	47	51	1	1	80	20	0	0
Wairoa River	21	58	20	1	0	0	8	92	100	0	0	0	55	40	5	0	43	37	16	4	60	36	3	0	72	19	7	2	34	60	4	1	31	57	11	0

Estuary	Macroalgae				Phytoplankton				Oxygen				Mud				aRPD				TOC				Seagrass				Macrobenthos				ETI band			
	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D
Waitakere River (Bethells Beach)	86	13	0	0	100	0	0	0	100	0	0	0	2	9	80	9	53	33	11	2	44	48	7	1	74	21	4	1	4	88	6	2	72	28	0	0
North Cove	97	3	0	0	60	40	0	0	100	0	0	0	90	9	1	0	75	22	3	0	86	14	0	0	96	2	1	1	47	51	1	1	63	37	0	0
Bon Accord Harbour	97	3	0	0	60	40	0	0	100	0	0	0	90	9	1	0	75	22	3	0	86	14	0	0	96	2	1	1	47	51	1	1	63	37	0	0
South Cove Harbour	97	3	0	0	60	40	0	0	100	0	0	0	90	9	1	0	75	22	3	0	86	14	0	0	96	2	1	1	47	51	1	1	63	37	0	0
Gardiner Gap	97	3	0	0	60	40	0	0	100	0	0	0	90	9	1	0	75	22	3	0	86	14	0	0	96	2	1	1	47	51	1	1	87	13	0	0
Islington Bay	97	3	0	0	60	40	0	0	100	0	0	0	90	9	1	0	75	22	3	0	86	14	0	0	96	2	1	1	47	51	1	1	63	37	0	0
Matiatia Bay	97	3	0	0	60	40	0	0	100	0	0	0	90	9	1	0	75	22	3	0	86	14	0	0	96	2	1	1	47	51	1	1	68	32	0	0
Owhanake Bay	97	3	0	0	60	40	0	0	100	0	0	0	90	9	1	0	75	22	3	0	86	14	0	0	96	2	1	1	47	51	1	1	68	32	0	0
Oneroa Bay	97	3	0	0	60	40	0	0	13	18	17	52	90	9	1	0	75	22	3	0	86	14	0	0	96	2	1	1	47	51	1	1	68	32	0	0
Mawhitipana Bay	97	3	0	0	60	40	0	0	13	18	17	52	90	9	1	0	75	22	3	0	86	14	0	0	96	2	1	1	47	51	1	1	63	37	0	0
Te Matuku Bay	97	3	0	0	60	40	0	0	100	0	0	0	90	9	1	0	75	22	3	0	86	14	0	0	96	2	1	1	47	51	1	1	87	13	0	0
Awaawaroa Bay	97	3	0	0	60	40	0	0	100	0	0	0	90	9	1	0	75	22	3	0	86	14	0	0	96	2	1	1	47	51	1	1	63	37	0	0
Rocky Bay	97	3	0	0	60	40	0	0	100	0	0	0	90	9	1	0	75	22	3	0	86	14	0	0	96	2	1	1	47	51	1	1	63	37	0	0
Putiki Bay	97	3	0	0	60	40	0	0	100	0	0	0	90	9	1	0	75	22	3	0	86	14	0	0	96	2	1	1	47	51	1	1	63	37	0	0
Huruhi Bay	97	3	0	0	60	40	0	0	13	18	17	52	90	9	1	0	75	22	3	0	86	14	0	0	96	2	1	1	47	51	1	1	63	37	0	0
Tryphena Harbour	97	3	0	0	60	40	0	0	13	18	17	52	90	9	1	0	75	22	3	0	86	14	0	0	96	2	1	1	47	51	1	1	68	32	0	0
Blind Bay	97	3	0	0	60	40	0	0	13	18	17	52	90	9	1	0	75	22	3	0	86	14	0	0	96	2	1	1	47	51	1	1	63	37	0	0
Whangaparapara Harbour	97	3	0	0	60	40	0	0	13	18	17	52	90	9	1	0	75	22	3	0	86	14	0	0	96	2	1	1	47	51	1	1	63	37	0	0
Port Fitzroy/Port Albercrombie	97	3	0	0	60	40	0	0	13	18	17	52	90	9	1	0	75	22	3	0	86	14	0	0	96	2	1	1	47	51	1	1	68	32	0	0
Katherine Bay	97	3	0	0	60	40	0	0	13	18	17	52	90	9	1	0	75	22	3	0	86	14	0	0	96	2	1	1	47	51	1	1	68	32	0	0
Rangiwhakaea Bay	97	3	0	0	60	40	0	0	13	18	17	52	90	9	1	0	75	22	3	0	86	14	0	0	96	2	1	1	47	51	1	1	68	32	0	0
Whangapoua Creek	93	7	0	0	48	44	8	0	100	0	0	0	90	9	1	0	74	23	3	0	85	14	0	0	96	2	1	1	47	51	1	1	85	15	0	0
Awana Bay	95	5	0	0	40	0	29	31	100	0	0	0	55	40	5	0	71	25	4	0	78	21	1	0	89	7	3	1	38	60	1	1	36	39	25	0

Estuary	Macroalgae				Phytoplankton				Oxygen				Mud				aRPD				TOC				Seagrass				Macrobenthos				ETI band			
	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D
Kaitoke Creek	95	5	0	0	100	0	0	0	100	0	0	0	55	40	5	0	71	25	4	0	78	21	1	0	89	7	3	1	38	60	1	1	78	22	0	0
Waitematā Harbour System	93	7	0	0	5	58	36	0	100	0	0	0	90	9	1	0	74	23	3	0	85	14	0	0	96	2	1	1	47	51	1	1	27	70	3	0
Tamaki River	93	7	0	0	5	58	36	0	100	0	0	0	90	9	1	0	74	23	3	0	85	14	0	0	96	2	1	1	47	51	1	1	84	16	0	0
Manukau Harbour System (MHS)	93	7	0	0	1	60	39	0	0	0	1	98	90	9	1	0	74	23	3	0	85	14	0	0	96	2	1	1	47	51	1	1	84	16	0	0