Proposed nutrient load limits for Otago estuaries

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Executive summary

Otago Regional Council require quantitative analyses of the effects of current nutrient loads on different receiving environments (rivers, lakes, estuaries) across the Otago region to support a regional objective and limit setting process with respect to water quality. In response, Land Water People (LWP) and NIWA are collaborating to provide these analyses, and guidance on the nutrient loads required to achieved desired ecological outcomes. NIWA's role is to develop simple estuary models that will predict the impact of nutrient loads on estuary trophic state and to recommend load limits corresponding to different trophic states.

This report describes the equations and parameterisations for models that can be used to predict the effects of different nutrient loads in 20 Otago coastal hydrosystems, along with predicted current eutrophication state. 'Coastal hydrosystem' is a term encompassing a wide range of coastal water bodies from coastal lakes and freshwater river mouths, to marine systems such as coastal embayments or harbours. In this report, the more widely recognised term estuary is used interchangeably with coastal hydrosystem. The response of estuaries to nutrient loads is based on the New Zealand Estuary Trophic Index (ETI) tool 1 dilution modelling approach. Current states were predicted using nutrient loads provided by LWP. A summary of these results is given in the table below.

Nutrient loads (total nitrogen and total phosphorus) corresponding to macroalgae and phytoplankton band thresholds have been calculated for each estuary and are provided in this report to assist in estimating changes in nutrient loads required to meet various management targets.

The dilution models have been calibrated for four of the estuaries, using results from previous studies. Improved estimates of nutrient load bands may be obtained by calibrating the dilution models using carefully designed estuary field studies.

Table 1-1: Estuary eutrophication susceptibility bands based on current loads.

Estuary	Overall ETI band	ETI band	Estuary	Overall ETI band	ETI band
Kakanui Estuary	1.0	**D**	Hoopers Inlet	0.24	**A**
Orore Creek Lagoon	1.0	**D**	Tomahawk Lagoon	1.00	**D**
Shag River Estuary	0.48	**B**	Kaikorai Estuary	1.00	**D**
Stony Creek Lagoon	1.0	**D**	Taieri Estuary	1.00	**D**
Pleasant River Estuary	0.72	**C**	Akatore Estuary	1.00	**D**
Waikouaiti Estuary	0.62	**C**	Tokomairiro Estuary	1.00	**D**
Blueskin Bay	0.45	**B**	Pounawea (Catlins) Estuary	0.57	**C**
Purakaunui Inlet	0.35	**B**	Tahakopa Estuary	0.77	**D**
Otago Harbour	0.20	**A**	Tautuku Estuary	0.68	**C**
Papanui Inlet	0.23	**A**	Waipati (Chaslands) Estuary	0.64	**C**

1 Introduction

Otago Regional Council (ORC) require assessments of load reductions to achieve National Policy Statement for Freshwater Management 2020 (NPSFM) National Objective Framework (NOF) attribute states in aquatic receiving environments of the Otago region. NOF attribute states have not yet been set for estuaries, but ORC wish to include estuaries in these assessments. In this report, we propose nutrient load thresholds equivalent to NOF attribute states for nitrogen and, where appropriate, phosphorus, based on eutrophication susceptibility bands developed for the New Zealand Estuary Trophic Index (Plew, Zeldis et al. 2020).

This report outlines the method for estimating nutrient load bandings, estimates the current eutrophic condition of Otago estuaries, then estimates nutrient load thresholds that correspond with thresholds between the ETI bands.

2 Methods

2.1 Estuary classification

Estuary classification is useful for assessments of eutrophication susceptibility where estuary types describe more than one physical parameter (e.g., average depth, intertidal area, and residence time) that mediate responses of estuary ecosystems to nutrient loads from land. Two typologies are used to classify coastal water bodies in this study. The first is the Estuary Trophic Index typology which consists of four types:

Shallow Intertidally Dominated Estuaries (SIDE) – generally short residence times, predominantly intertidal, usually well flushed with a large tidal prism relative to freshwater inflow. Sensitive to macroalgal blooms.

Shallow Short Residence Time River Estuaries (SSRTRE) – tidal rivers that may include well flushed adjoining lagoons. Characterised by limited intertidal area and high freshwater input relative to volume. Often with low salinities which can restrict macroalgal growth, or high velocities which detach or scour limiting accumulation.

Deep Sub-tidally Dominated Estuaries (DSDE) – subtidal, moderately deep or deep with moderate or long residence times. Sensitive to opportunistic macroalgal blooms on intertidal and shallow areas, and phytoplankton blooms in deeper waters

Coastal Lakes – freshwater or brackish water bodies that are normally closed to the sea or have little or intermittent seawater input. Long residence times and sensitive to phytoplankton blooms.

Subtypes of SIDEs and SSRTREs that intermittently close to the sea are considered Intermittently Closed and Open Estuaries (**ICOE**). The normal state of ICOEs is open, in contrast to coastal lakes which are normally or always closed.

The second typology is the New Zealand Coastal Hydrosystem (NZCHS) which provides greater granularity, consisting of 11 main classes, some of which contain subclasses (Hume, Gerbeaux et al. 2016). The 11 classes span from lacustrine through to riverine, estuarine and marine systems. The names of the NZCHS classes are descriptive, and NZCHS classes can be related to ETI types (Hume 2018) with the most common[1] matches indicated in Table 2-1. While estuaries are technically a subset of coastal hydrosystems (those in which salinity is between marine and freshwater values), "estuary" is a more widely recognised term and is used here to encompass all coastal hydrosystems, including those that are predominantly freshwater.

[1] The relationship between NZCHS class and ETI type is not one to one. The NZCHS and ETI use different characteristics to classify hydrosystems, and classification of hydrosystems is not necessarily clear-cut for either typology.

Table 2-1: New Zealand Coastal Hydrosystem (NZCHS) classes, and the Estuary Trophic Index (ETI) estuary types that most commonly corresponds to each NZCHS class. SSRTRE = shallow short residence time river estuary, SIDE = shallow intertidally dominated estuary, DSDE = deep sub-tidally dominated estuary.

	NZCHS class	ETI type
1.	Damp sand plain lake	Coastal Lake
2.	Waituna-type lagoon	Coastal Lake
3.	Hāpua-type lagoon	SSRTRE
4.	Beach stream	SSRTRE
5.	Freshwater river mouth	SSRTRE
6.	Tidal river mouth	SSRTRE
7.	Tidal Lagoon	SIDE
8.	Shallow drowned valley	SIDE
9.	Deep drowned valley	DSDE
10.	Fjord	DSDE
11.	Coastal embayment	DSDE

2.2 Otago estuaries

Twenty-two Otago coastal hydrosystems are identified in the NZCHS (Hume, Gerbeaux et al. 2016), which is largely based on the "Coastal Explorer Database" compiled by Hume, Snelder et al. (2007). This database includes estimates of key physical parameters including volume, area, intertidal proportion and tidal prism. These parameters, along with shape files of estuary perimeters, were estimated from hydrographic charts, topographic maps, aerial images and various reports (Hume, Snelder et al. 2007). The names of the hydrosystems in the NZCHS do not always match those in common use, and few, if any, appear in the New Zealand Gazetteer. In this report, names are based on those believed to be in common use, or the common name included e.g., Pouanwea (Catlins) Estuary. 'Estuary' is used for systems known to be estuarine, and that do not contain 'inlet', 'bay' or 'harbour' in their name. 'Lagoon' is used for those systems expected to be freshwater dominated. The terms 'river' and 'creek' are generally, but not always, excluded unless the first part of the name is an adjective (Shag River Estuary is the exception). The division is arbitrary, and the names used here should not be considered the official names.

There are a wide variety of coastal hydrosystem sizes and types in the Otago Region (Table 2-2). The northern-most is the Kakanui Estuary, and the southernmost the Waipati Estuary (also known as Chaslands Estuary) on the border between the Otago and Southland regions (Figure 2-1). The largest system is the Otago Harbour (4790 hectares), a deep drowned valley with relatively low river input in relation to its size and likely to be ocean dominated. The Orore Creek Lagoon is the smallest at 8.5 hectares. It is classified as a Beach Stream in the NZCHS and is likely non-tidal and freshwater dominated. Between these extremes are other, likely freshwater dominated, beach streams; tidal river mouths which range between freshwater dominated systems and estuarine; and tidal lagoons characterised by high proportions of intertidal areas and high tidal exchange with the ocean. Known ICOEs are the Kakanui, Kaikorai and Tokomairiro estuaries. Other Otago systems may also be ICOEs but ICOE status is not recorded in the NZCHS database.

Two of the coastal hydrosystems are excluded from further analysis in this report. The Waikouati/Hawksbury Lagoon is a highly modified system split by causeways which affect the circulation within the lagoon. There is insufficient data in the NZCHS database to calculate the flushing time of such a system. The Clutha River is also excluded because the extent of the estuarine portion of the river is not well defined. The shape file produced by Hume, Snelder et al. (2007) shows the Clutha River Estuary extending as far upstream as Balclutha, which likely overestimates the extent of any saline intrusion by several kilometres. The Clutha River has a very high flow rate (mean flow of 575 $m^3 s^{-1}$) suggesting its lower reaches are likely to be freshwater dominated rather than estuarine.

Some of the properties in the Coastal Explorer database appeared to be incorrect or outdated, and in some cases the shape files poorly matched recent satellite imagery (shape files for each of the coastal hydrosystems are plotted over satellite imagery in Appendix A). For these estuaries, area at high tide, intertidal area, volume, and tidal prism were re-calculated. These estimates are based on satellite imagery using images from what appear to be high and low tide to calculate areas. Tidal prisms were estimated from difference in volume between high and low tide, assuming that the tidal range in the estuary was a portion (default 75%) of spring tide at the coast. NIWA have conducted recent surveys for five of the coastal hydrosystems during projects for ORC (Kakanui Estuary, Shag River Estuary, Kaikorai Estuary, Tokomairiro Estuary, Pounawea (Catlins) Estuary). Data from those studies are used in place of values from Coastal Explorer.

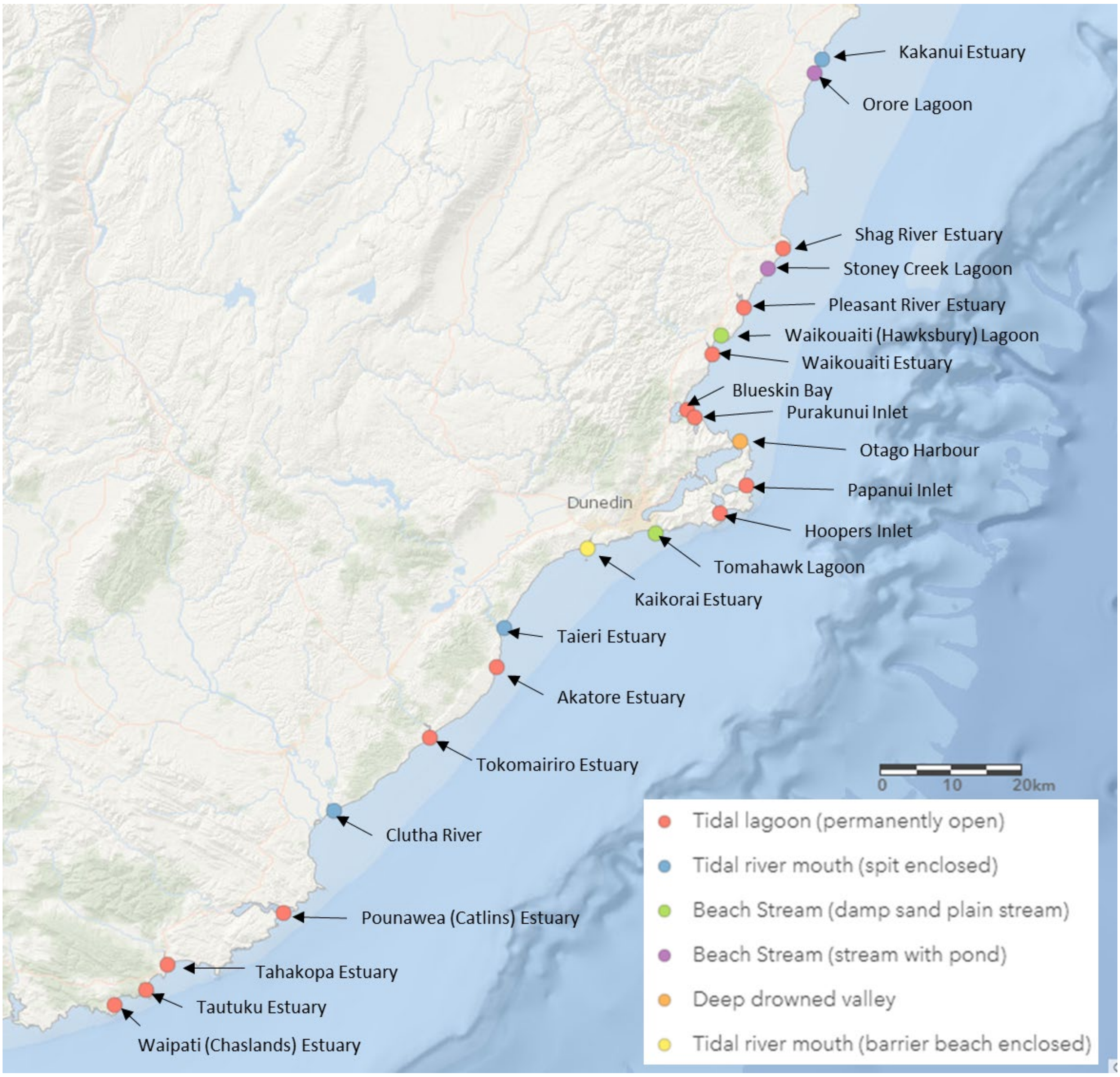

Figure 2-1: Locations of Otago coastal hydrosystems. The coastal hydrosystems shown are those identified in the New Zealand Coastal Hydrosystems database.

Table 2-2: Physical characteristics of Otago coastal hydrosystems. Estuary Number is from the Coastal Explorer database (Hume, Snelder et al. 2007); New Zealand Coastal Hydrosystem (NZCHS) code, class from the NZCHS database; and ETI type based on Plew, Zeldis et al. (2020) and Robertson, Stevens et al. (2016a). Waikouaiti (Hawsbury) Lagoon and Clutha River (in *italics*) are not considered further in this study.

Estuary No.	Coastal Hydrosystem	NZCHS code	NZCHS class	ETI type	Volume (m^3)	Tidal Prism (m^3)	Area (m^2)	Mean flow ($m^3\ s^{-1}$)	Feb flow seasonality	Inter-tidal (%)
1047	Kakanui Estuary	6B	Tidal river mouth (spit enclosed)	SSRTRE	455,441	246,057	190,707	6.283	0.808	21.2
1048	Orore Lagoon	4C	Beach Stream (stream with pond)	COASTAL LAKE	84,727	0	84,795	0.118	0.577	0.08
1049	Shag River Estuary	7A	Tidal lagoon (permanently open)	SIDE	1,352,800	1,117,500	1,223,500	3.091	0.616	67.5
1050	Stony Creek Lagoon[2]	4C	Beach Stream (stream with pond)	COASTAL LAKE	160,907	0	155,169	0.062	0.553	0
1051	Pleasant River Estuary[3]	7A	Tidal lagoon (permanently open)	SIDE	1,200,830	921,448	1,333,119	0.981	0.572	85.3
1052	*Waikouaiti (Hawksbury) Lagoon*	*4B*	*Beach Stream (damp sand plain stream)*	*COASTAL LAKE*	*24,857*	*0*	*494,178*	*0.038*	*0.560*	*94.97*
1053	Waikouaiti Estuary	7A	Tidal lagoon (permanently open)	SIDE	2,180,631	1,359,584	1,272,547	3.070	0.542	67.74
1054	Blueskin Bay	7A	Tidal lagoon (permanently open)	SIDE	7,559,191	5,787,209	6,230,597	0.780	0.515	85.78
1055	Purakaunui Inlet	7A	Tidal lagoon (permanently open)	SIDE	1,294,680	1,027,041	1,130,231	0.051	0.509	88.16
1056	Otago Harbour	9	Deep drowned valley	DSDE	184,773,975	60,304,035	47,912,396	1.312	0.497	45.32
1057	Papanui Inlet	7A	Tidal lagoon (permanently open)	SIDE	3,968,608	3237684	3,629,214	0.054	0.555	89.93

[2] Coastal Explorer gives a tidal prism of 140,637 m^3 and 86% intertidal area for Stoney Creek Lagoon. However, satellite imagery shows that this Beach Stream has only intermittent connection with the ocean and is likely to have minimal and infrequent sea water input. In this study, Stoney Creek is modelled as a coastal lake, and assigned 0% intertidal area and 0 m^3 tidal prism.

[3] Pleasant River high tide and low tide surface areas were measured from satellite imagery dated 6 July 2019 and 27 February 2018. Intertidal area was increased from 75.8% to 85.3%, high tide area from 973,105 m^2 to 1,333,119 m^2, volume decreased from 1,443,302 m^3 to 1,200,837 m^3, and tidal prism from 971541 to 921,448 m^2.

Estuary No.	Coastal Hydrosystem	NZCHS code	NZCHS class	ETI type	Volume (m^3)	Tidal Prism (m^3)	Area (m^2)	Mean flow ($m^3 s^{-1}$)	Feb flow seasonality	Inter-tidal (%)
1058	Hoopers Inlet	7A	Tidal lagoon (permanently open)	SIDE	3,636,671	3246593	3,750,748	0.067	0.549	94.8
1059	Tomahawk Lagoon	4B	Beach Stream (damp sand plain stream)	COASTAL LAKE	193,787	0	197,139	0.062	0.517	1.7
1060	Kaikorai Estuary	6C	Tidal river mouth (barrier beach enclosed)	SSRTRE	317,000	293,525	759,050	0.504	0.489	97
1061	Taieri Estuary	6B	Tidal river mouth (spit enclosed)	SSRTRE	3,915,460	2,511,015	1,559,802	45.55	0.502	9.96
1062	Akatore Estuary[4]	7A	Tidal lagoon (permanently open)	SIDE	324,280	304,941	383,498	0.693	0.574	74.9
1063	Tokomairiro Estuary[5]	7A	Tidal lagoon (permanently open)	SSRTRE	1,459,000	760,000	1,077,000	2.239	0.577	23
1064	*Clutha River*	*6B*	*Tidal river mouth (spit enclosed)*	*SSRTRE*	*16,401,711*	*10,535,431*	*6,201,797*	*617*	*0.520*	*5.41*
1066	Pounawea (Catlins) Estuary[6]	7A	Tidal lagoon (permanently open)	SIDE	14,156,300	11,763,600	8,128,900	6.956	0.561	73.1
1067	Tahakopa Estuary	7A	Tidal lagoon (permanently open)	SSRTRE	1,939,721	1,345,484	860,340	7.166	0.611	30.93
1068	Tautuku Estuary	7A	Tidal lagoon (permanently open)	SIDE	1,338,632	838,250	650,185	1.325	0.596	61.52
1069	Waipati Estuary[7]	7A	Tidal lagoon (permanently open)	SIDE	546,675	465,021	545,140	1.644	0.581	79.8

[4] Akatore Estuary high tide and low tide surface areas were measured from satellite imagery dated 16 March 2016 and 1 Sept 2019. Intertidal area was increased from 34.1% to 74.9%, high tide area from 328,983 m^2 to 383,498 m^2, volume reduced from 895,893 to 324,280 m^3 and tidal prism from 462,359 m^3 to 304,941 m^3.
[5] Estuary surveyed by NIWA in 2019 (Plew, Dudley et al. 2019b).
[6] Estuary surveyed by NIWA in 2018 (Plew and Dudley 2018a).
[7] Waipati Estuary high tide and low tide surface areas were measured from satellite imagery dated 19 March and 21 April 2019. Intertidal area was increased from 33.8% to 79.8%, high tide area from 459,476 m^2 to 545,140 m^2, volume reduced from 1,330,563 m^3 to 546,675 m^3, and tidal prism from 722,401 m^2 to 465,021 m^2.

2.3 Eutrophication susceptibility

2.3.1 Overview

The physical characteristics of estuaries strongly influence their response to nutrient loads. Geometric and bathymetric characteristics affect how much mixing between river and ocean water occurs within the estuary, and whether the estuary is likely provide suitable habitat for macroalgae (with large shallow or intertidal areas), or more likely to be affected by phytoplankton (deeper, long flushing times).

The response of estuaries to nutrients is complex. Many physical, biological, and geochemical processes are involved; several of which are poorly understood or difficult to model. While a variety of tools are available to predict ecological or morphological response, such as complicated and detailed coupled hydrodynamic-biogeochemical modelling, the input data required, cost and time required to implement such models can be prohibitive. As an alternative, NIWA produced reasonably simple, semi-empirical models for predicting the response of estuaries to nutrients as part of the New Zealand Estuary Trophic Index (ETI) tools project.

The ETI was developed to assist New Zealand's regional councils manage and protect estuary health. Development started in 2015, funded by an Envirolink Tools Grant (Contract No. C01X1420). The project team included scientists from regional councils, environmental consultants and NIWA. The ETI provides three freely available tools. Tool 1 predicts the susceptibility of estuaries to eutrophication[8], tool 2 assesses the current state of estuaries based on observations[9], and tool 3 is a Bayesian belief network that predicts estuary state using a combination of modelled inputs and observations where available[10].

The methods used to estimate nutrient load bands are based on ETI tool 1, described by Plew, Zeldis et al. (2020). ETI tool 1 predicts the response of primary producers (macroalgae and phytoplankton) to nutrient loads. Excessive growth of macroalgae or phytoplankton have both a nuisance effect and cause degraded conditions such as organic enrichment and poor oxygenation of sediments, imparted microbenthic health, water column deoxygenation, and loss of keystone species and important habitats such as seagrass.

ETI tool 1 is based on a dilution modelling approach that predicts potential nutrient concentrations[11] within and flushing times of estuaries. These can be related to likely expressions of eutrophication in the form of macroalgal or phytoplankton blooms (Plew, Zeldis et al. 2020). The dilution model provides a whole of estuary, steady-state prediction of eutrophication intended to be used primarily as a screening to prioritise further work but can also be used to estimate nutrient load bands likely to result in different levels of eutrophication.

[8] https://shiny.niwa.co.nz/Estuaries-Screening-Tool-1/
[9] https://shiny.niwa.co.nz/Estuaries-Screening-Tool-2/
[10] https://shiny.niwa.co.nz/Estuaries-Screening-Tool-3/
[11] Potential nutrient concentrations are the concentrations that would occur in the absence of non-conservative processes such as uptake by algae, denitrification, or other biogeochemical processes (Plew, Zeldis et al. 2018; Plew, Zeldis et al. 2020). Observed nutrient concentrations (such as measured in water quality sampling) may often be lower than potential concentrations due to these processes, especially during periods of high seasonal growth and nutrient depletion (Bricker et al. 2003). Potential concentration is directly linked to the nutrient load, and has found to be a better predictor of phytoplankton biodiversity and biomass (National Research Council 2000; Ferreira, Wolff et al. 2005) than observed concentrations, particularly during nutrient limited phases of the annual cycle (Bricker et al. 2003).

2.3.2 Dilution modelling

Susceptibility to eutrophication was assessed using the ETI tool 1 dilution modelling approach (Plew, Zeldis et al. 2020). A single-compartment dilution model was created for each estuary to determine the potential TN and TP concentrations and flushing time. The single-compartment dilution model is described in detail elsewhere (Plew, Zeldis et al. 2018; Plew, Dudley et al. 2020; Plew, Zeldis et al. 2020), but a summary is provided below.

The estuary is modelled as a steady state, continuously stirred container, receiving inputs from the freshwater sources, and exchanging water with the ocean. The tidal flow in and out of the estuary is averaged over the tidal period *T*, and the concentration of a tracer in the estuary is solved for the estuary at high tide. The mass balance for the tracer is illustrated in Figure 2-2.

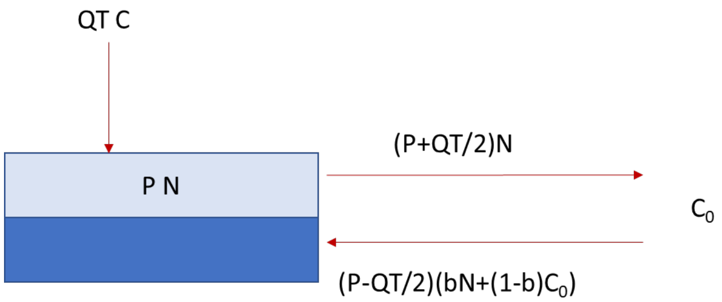

Figure 2-2: Mass balance diagram for the single-compartment estuary dilution model.

The terms in Figure 2-2 are as follows:

Q = freshwater inflow (m^3/s).

T = tidal period (12.42 x 3600 s).

P = tidal prism, difference in volume between high and low tide (m^3).

N = concentration of the tracer in the estuary (mg/m^3).

C = concentration of the tracer in the freshwater inflow (mg/m^3).

C_0 = concentration of the tracer in the ocean (mg/m^3).

b = tuning factor (-).

The tuning factor b is determined using measured salinity data from the estuary, with $N = S$ (salinity in the estuary), $C = 0$ (zero salinity in the freshwater inflow), and $C_0 = S_0$ (ocean salinity), using the inflow Q and tidal prism P at the time the estuary-averaged salinity was measured.

The solution for b is:

$$b = \frac{P - QT\left(\frac{S_0}{S_0 - S} - \frac{1}{2}\right)}{\frac{QT}{2} - P}$$

The tuning factor can then be used to calculate a dilution factor for other flows or tidal prisms:

$$D = \frac{P(1-b) + \frac{QT}{2}(1+b)}{QT}$$

The dilution factor is related to the freshwater fraction *f*:

$$f = \frac{1}{D}$$

The concentration of the tracer (or potential nutrient concentration) is then calculated as:

$$N = Cf + C_0(1-f)$$

Estuary flushing time T_F is defined as the time taken to replace the freshwater within the estuary:

$$T_F = \frac{fV}{Q}$$

where *V* is the estuary volume at high tide.

The tuning factor *b* accounts for incomplete mixing and return flow (some of the water that flows out of the estuary on the ebb tide returns to the estuary on the flood tide). This tuning factor is likely unique to each estuary and can be calculated from salinity observations. As suitable salinity data are not available for many estuaries, Plew, Zeldis et al. (2018) made a predictor for the tuning factor as a function of the ratio of freshwater inflow of a tidal period to tidal prism. This predictor has been revised (Plew 2020) using additional data collected from Otago and Southland estuaries (Plew and Dudley 2018a; Plew, Dudley et al. 2019b; Plew, Dudley et al. 2019a; Plew, Dudley et al. 2020). The revised predictor is used here to estimate a return flow factor for estuaries where observational data are not available (Figure 2-3).

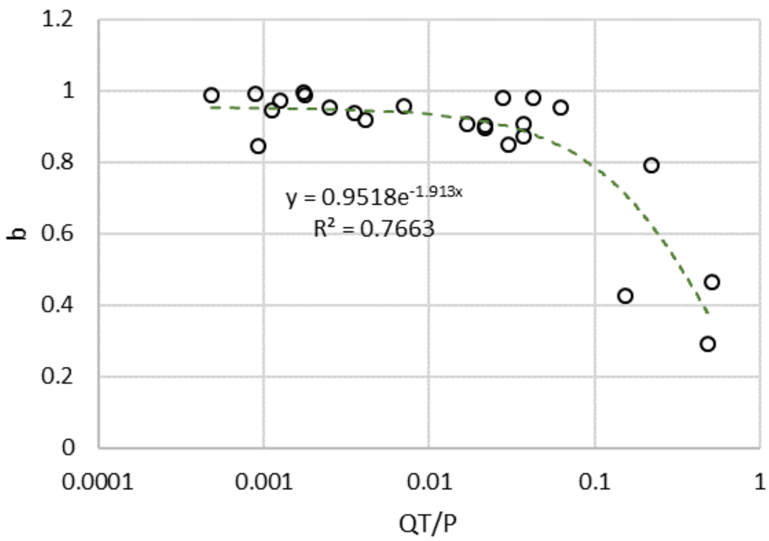

Figure 2-3: Estuary tuning factor as a function of freshwater inflow and tidal prism. Original figure from Plew, Zeldis et al. (2018) updated with recent data from Otago and Southland estuaries.

Calculations of potential nutrient concentrations for determining eutrophication susceptibility use tidal prism at spring tide and mean flow (Plew, Zeldis et al. 2020). Salinity observations used to derive tuning factors (for those estuaries where data are available) are seldom collected under these conditions. As noted above, unpublished observational data suggests that within an estuary, the tuning factor is sensitive to changes in freshwater inflow and tidal prism, decreasing with increasing *QT/P*. While the form of the relationship between *QT/P* and *b* for individual estuaries is not known, we assume that it follows a similar exponential relationship to that shown in Figure 2-3. For estuaries with return-flow factors calculated from salinities, we calculate a reference return flow factor at zero inflow:

$$b_0 = b_{obs} e^{1.913\frac{Q_{obs}T}{P_{obs}}}$$

which is then used to calculate the return flow factor at different inflows or tidal prisms:

$$b = b_0 e^{-1.913\frac{QT}{P}}$$

For estuaries where the reference return flow factor has not been determined, the default value is 0.952 (Figure 2-3).

2.3.3 Macroalgal susceptibility

The susceptibility to macroalgae blooms is predicted using an empirical relationship developed from observations from 21 New Zealand estuaries. Macroalgal levels were assessed using the Opportunistic Macroalgal Blooming Tool (OMBT) Ecological Quality Rating (EQR), which is a combined metric based on both biomass and spatial measures (Water Framework Directive - United Kingdom Advisory Group 2014). EQR is calculated from observations of % cover of available intertidal habitat, affected area with > 5% macroalgae cover, average biomass, and % cover with algae > 3 cm deep. Biomass thresholds included in the OMBT were lowered for use in New Zealand (Plew, Zeldis et al. 2020) based on data from shallow intertidal estuaries in New Zealand (Robertson, Stevens et al. 2016b) and similar estuaries in California (Green, Sutula et al. 2014; McLaughlin, Sutula et al. 2014; Sutula, Green et al. 2014). EQR scores range from 0 (severely impacted) to 1 (no impact). EQR scores are categorised into four bands (A to D). Descriptions of the expected ecological conditions corresponding to each banding are given in Table 2-3.

EQR scores are plotted against calculated potential total nitrogen (TN) concentrations for the 21 estuaries in Figure 2-4. A linear least-squares fit is used to determine potential TN thresholds that correspond with EQR values of 0.8, 0.6 and 0.4 (the thresholds between bands, Table 2-3). The potential concentrations corresponding to A/B, B/C and C/D thresholds are 82, 202 and 321 mg m^{-3}, respectively. These are rounded to 80, 200 and 320 mg m^{-3}.

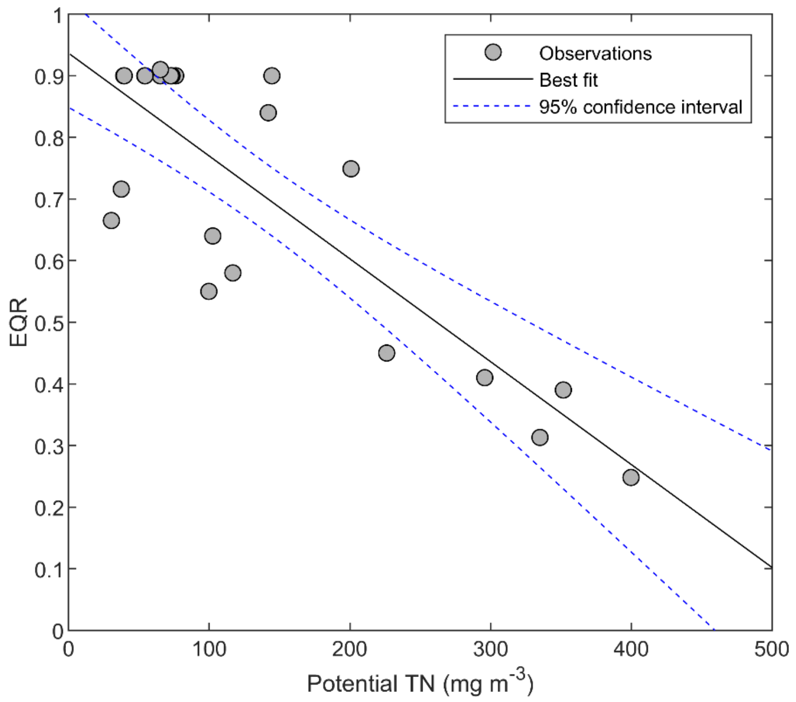

Figure 2-4: Observations of EQR vs Potential TN from 22 New Zealand estuaries. Grey circles show observed EQR and corresponding potential TN concentrations, the black line is a least-squares best fit linear regression, and the blue lines show a 95% confidence interval for the regression. Adapted from Plew, Zeldis et al. (2020).

Table 2-3: Macroalgal bands with corresponding EQR ratings, potential (TN) ranges, and a description of expected ecological state for each band. Potential TN concentrations are based on annual loads and annual mean flows. Descriptions of expected ecological states are adapted from Robertson, Stevens et al. (2016b).

Macroalgae susceptibility band	A	B	C	D
Eutrophication level	Minimal	Moderate	High	Very high
Ecological Quality Rating	1.0 > EQR ≥ 0.8	0.8 > EQR ≥ 0.6	0.6 > EQR ≥ 0.4	EQR < 0.4
Equivalent ETI score	0 – 0.25	0.25 – 0.50	0.50 – 0.75	0.75 – 1.0
Potential TN concentration (mg m^{-3})	TN ≤ 80	80 < TN ≤ 200	200 < TN ≤ 320	TN > 320
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 sulphidic conditions near the sediment surface

Macroalgae growth is inhibited by low salinity (Choi, Kang et al. 2010; Rybak 2018). In the ETI tool 1 approach, macroalgal blooms are considered to not occur if the salinity is < 5 (Plew, Zeldis et al. 2020). However, this hard threshold may underpredict macroalgal response in some low salinity systems. Recent experiments on *Agarophyton* spp. (formerly *Graciliaria*) from estuaries in southern New Zealand show growth rates reduce at low salinity, with marked reductions at salinities less than ~ 5 ppt and growth ceasing at salinities below ~ 1 ppt (Dudley, Barr et al. submitted). For this project and in similar work for Environment Southland (Plew 2020), the prediction of macroalgae EQR is modified to decrease macroalgae abundance (i.e., increase EQR) for salinities less than 5 ppt.

If salinity S < 5, then:

$$EQR' = 1 - \frac{S}{5}(1 - EQR)$$

Else:

$$EQR' = EQR$$

2.3.4 Phytoplankton susceptibility

Phytoplankton susceptibility is calculated using an analytical growth model that predicts the likely maximum chlorophyll-*a* concentration as a function of potential TN and TP concentrations and flushing time (Figure 2-5), (Plew, Zeldis et al. 2020). This analytical model is derived in the same manner as the dilution model described above, but with additional terms for phytoplankton and nutrient concentrations, growth of phytoplankton, and uptake of nutrients (Plew, Zeldis et al. 2020). Phytoplankton blooms are more common during summer months when water temperatures are higher, day length is longer (hence greater light availability), and inflows are generally lower resulting in longer flushing times. For this reason, summer inflows are used when calculating potential nutrient concentrations and flushing times. Summer flows are estimated by scaling the annual mean flow by the February seasonality factor (the ratio of February mean flow to annual mean flow) (Booker and Woods 2014), available from NZRiverMaps (Booker and Whitehead 2017). The TN and TP concentrations of the freshwater inflows are calculated from annual load and mean flow, and do not incorporate any seasonality in riverine nutrient concentrations.

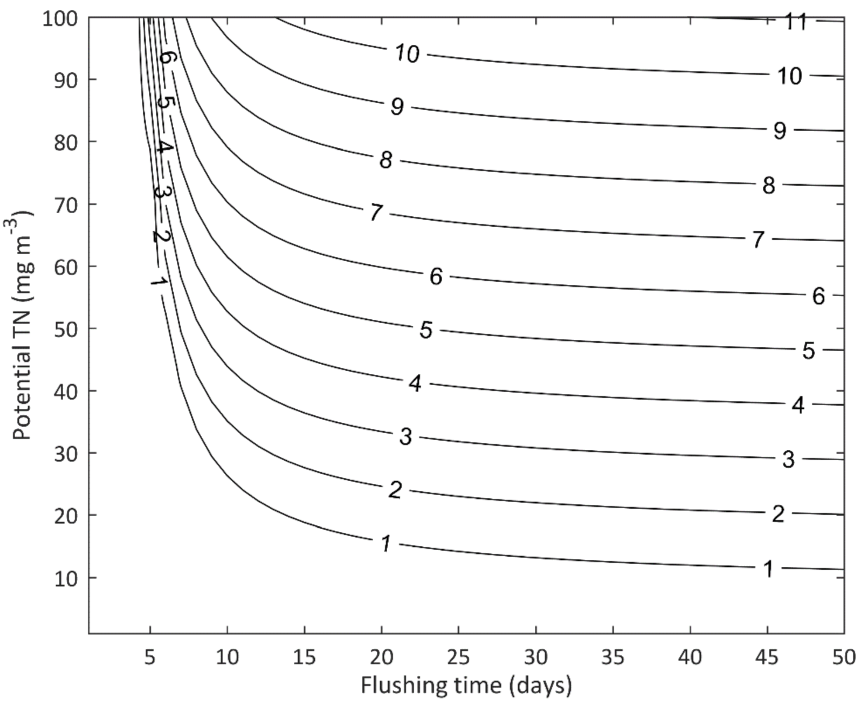

Figure 2-5: Contours of predicted chlorophyll-*a* concentrations (µg/l) as a function of the potential total nitrogen concentration and estuary flushing time. The graph shows modelled chlorophyll concentrations when phosphorus is not limiting and assumes a specific growth rate k = 0.3 d^{-1} and a half saturation coefficient for growth response to nitrogen of 35 mg m^{-3}. Phytoplankton does not accumulate in the estuary if the flushing time is shorter than the doubling time (1/k), and steady state concentrations are proportional to potential TN concentrations as flushing time increases.

The predicted chlorophyll-*a* concentrations (e.g., Figure 2-5) represent the upper limit (maximum) of phytoplankton biomass expected to be obtained in the estuary under ideal conditions. Susceptibility bandings applied to these predictions are based on thresholds developed for the 90th percentile of monthly observations. For euhaline (salinity > 30) and meso/polyhaline estuaries (5 ≤ salinity < 30), the thresholds are based on Revilla, Franco et al. (2010) for estuaries in Basque[12] (due to a lack of NZ specific data), while the New Zealand National Policy Statement for Freshwater Management (Ministry for the Environment 2018) bands are used for coastal lakes and brackish estuaries (salinity < 5).

While the dilution modelling approach does estimate salinity, in this study the bandings for meso/polyhaline estuaries are applied to all tidal lagoons (SIDEs) and tidal river mouths (SSRTREs), the oligohaline bands applied to beach streams (coastal lakes), and the euhaline bands applied to Otago Harbour (the only DSDE).

Note that the thresholds for euhaline and meso/polyhaline estuaries are slightly higher than those used described in the ETI (Robertson, Stevens et al. 2016b; Plew, Zeldis et al. 2020), but are consistent with those applied in Southland (Plew 2020).

Revilla, Franco et al. (2010) provide five class boundaries; the two highest concentration bands are combined in the ETI and this project to obtain four bands (Table 2-4).

Table 2-4: Bandings for chlorophyll-*a* concentrations (µg/l) predicted using the phytoplankton susceptibility model. Bandings differ depending on estuary salinity. The upper bound values are used to assign an equivalent ETI score of 1.0, indicating a highly eutrophic state.

ETI Band	Class boundaries	Equivalent ETI score	Euhaline (>30 ppt)	Meso/Polyhaline (≥5-30 ppt)	Oligohaline/coastal lake (<5 ppt)
A	High	0-0.25	≤4 µg/l	≤8 µg/l	≤10 µg/l
B	Good	0.25-0.50	>4 and ≤8 µg/l	>8 and ≤12 µg/l	>10 and ≤25 µg/l
C	Moderate	0.50-0.75	>8 and ≤12 µg/l	>12 and ≤16 µg/l	>25 and ≤60 µg/l
D	Poor + bad	0.75-1.0	>12 µg/l	>16 µg/l	>60 µg/l
Upper bound		*1.0*	*20 µg/l*	*48 µg/l*	*120 µg/l*

2.3.5 Conversion to equivalent ETI scores

To allow a comparison between phytoplankton and macroalgal indicators, and also to provide a predictor of the overall ecological state of an estuary, an equivalent ETI score is calculated for each of the primary indicators. This conversion also normalises for chlorophyll-*a* bandings that differ based on salinity (Table 2-4). Note that an actual ETI score (Robertson, Stevens et al. 2016b; Zeldis, Whitehead et al. 2017) is based on observed primary indicators (macroalgae or phytoplankton) and secondary indicators (e.g., oxygen, apparent redox potential discontinuity, macrobenthos condition); however, here we predict only the primary indicators.

Macroalgal EQR is converted to an equivalent macroalgal ETI score (ETI_M) by linear interpolation. Ignoring other indicators, an EQR of 1.0 equates to an ETI score of 0, and EQR of 0.2 to an ETI score of 1.0. The conversion is:

[12] The ETI has slightly different thresholds between euhaline A/B and meso/polyhaline A/B and B/C bands, but the C/D threshold which define 'national bottom lines' are the same.

$$ETI_M = \frac{(1 - EQR)}{0.8}$$

with a maximum of ETI_M = 1.0.

In recent studies of Otago and Southland estuaries, we have found that our macroalgal predictor tends to over-predict EQR in river-type estuaries (SSRTRE) where high velocities causing detachment or scour may be restricting macroalgal biomass. Yet, in these same estuaries, the observed ETI tool 2 score (incorporating secondary indicators such as sediment chemistry and oxygenation) often shows good agreement to the equivalent ETI score based on predicted macroalgal EQR (see for example the Tokomairiro, Kaikorai and Shag River estuaries in Figure 2-6). In some cases, this may be due to microphytobenthos which likely respond to nutrients in a similar manner to macroalgae, causing similar degradation in sediment chemistry. Toetoes (Fortrose) Estuary is an outlier in that both its EQR score and ETI score are better than expected for the potential TN concentration.

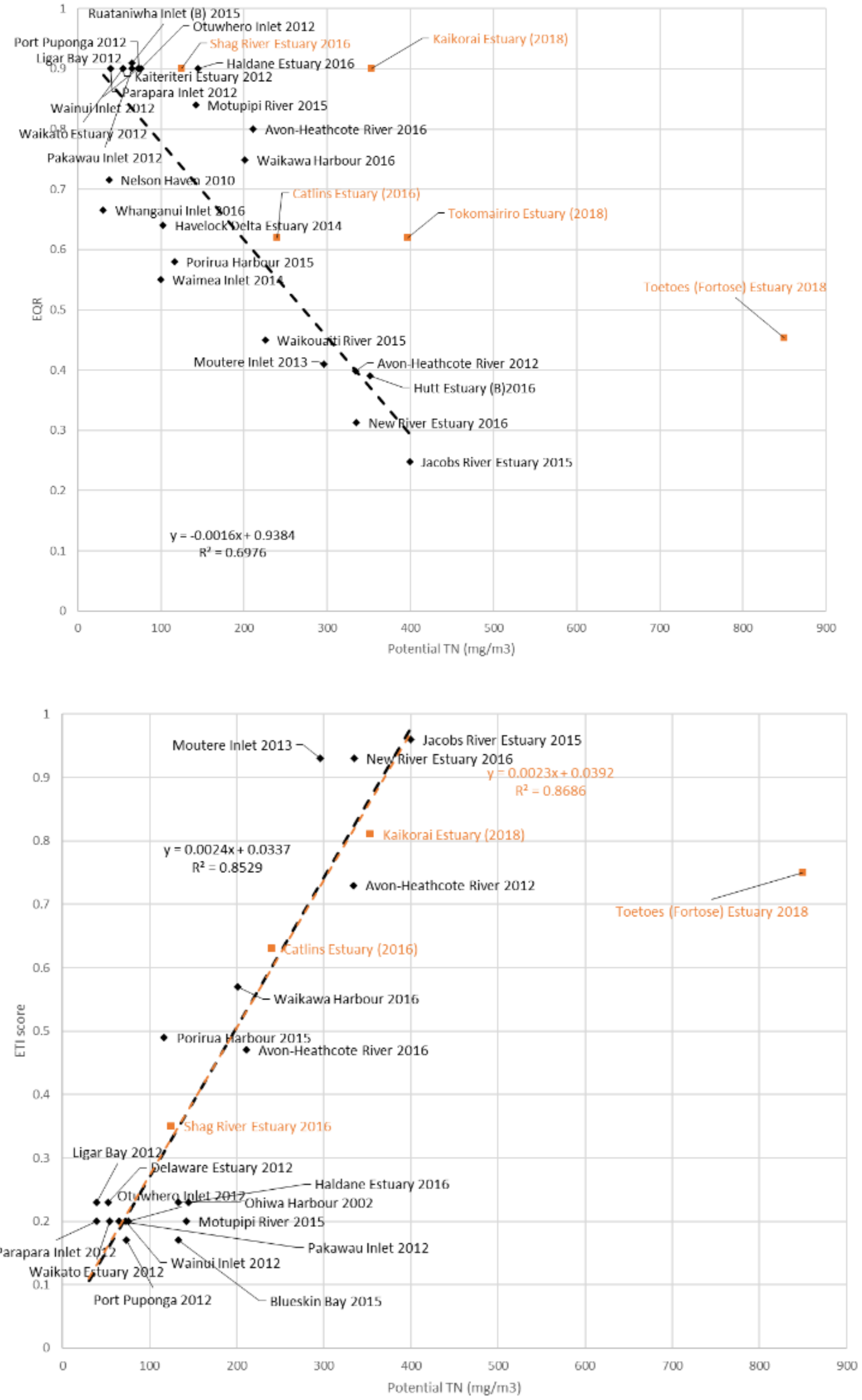

Figure 2-6: Observed EQR vs potential TN, and observed ETI score vs potential TN. Black symbols show data included in the development of the ETI bands for TN, and orange symbols show more recent data collected from other estuaries. In most cases, the observed ETI score lies closer to the regression line than the EQR score.

Predicted chlorophyll-*a* concentrations are converted to an equivalent ETI score (ETI_P) by linear interpolation between threshold values that bracket that concentration.

$$ETI_P = ETI_{lower} + (ETI_{upper} - ETI_{lower})\frac{CHL - CHL_{lower}}{CHL_{upper} - CHL_{lower}}$$

Where:

CHL = predicted chlorophyll-*a* concentration

CHL_{upper} = chlorophyll-*a* band upper limit

CHL_{lower} = chlorophyll-*a* band lower limit

ETI_{upper} = ETI score corresponding to the band upper limit

ETI_{lower} = ETI score corresponding to the band lower limit

For example, a predicted chlorophyll-*a* concentration of 10 μg/l in an euhaline estuary would give an equivalent phytoplankton ETI_P score of:

ETI_P = 0.50 + (0.75-0.50) × (10-8)/(12-8) = 0.625

Where predicted chlorophyll-*a* values exceed the C/D threshold, the linear interpolation uses an upper bound concentration, which for euhaline and meso/polyhaline estuaries have been defined by making the Poor/Bad class boundaries of Revilla, Franco et al. (2010) the mid-point between the C/D chlorophyll-*a* threshold and the upper bound. For oligohaline estuaries/coastal lakes, the upper bound is set at twice the C/D threshold. If predicted concentrations exceed the upper bound, then an ETI_P score of 1.0 is assigned. This selection of upper bounds only affects the prediction of an ETI_P score at higher chlorophyll-*a* concentrations and does not impact the main goal of this study, which is to determine the catchment nutrient loads that correspond to each ETI band.

2.3.6 Overall susceptibility

The ETI tool 1 determines the overall eutrophication susceptibility of an estuary using either the macroalgal or phytoplankton susceptibility, depending on the characteristics of the estuary.

- Estuaries with large intertidal areas (>40% intertidal) are most susceptible to macroalgal blooms. Their extensive intertidal and shallow areas provide surfaces where macroalgae can grow and accumulate. While larger systems may have long enough flushing times to allow phytoplankton to grow, secondary indicators of phytoplankton blooms such as low water column oxygen levels are not common because, being shallow, they are generally vertically well-mixed.
- Estuaries with low intertidal area (<5%) tend to have little area available where macroalgae can become established and impacts of excessive macroalgal growth are confined to small areas. Phytoplankton blooms are of more concern in these systems which are generally sub-tidal or deep and include coastal lakes.
- Estuaries with intermediate (5%-40%) may be suspectable to either or both of macroalgal and phytoplankton blooms. For these estuaries, the higher (worst) of the macroalgal or phytoplankton indicators is used.

The overall predicted ETI score is selected from the equivalent ETI scores for macroalgae and phytoplankton as appropriate for each estuary, as described above.

Estuary type may also be considered, in addition to intertidal area, when choosing whether macroalgal or phytoplankton susceptibility determines the overall eutrophication susceptibility. Generally, the ETI typology agrees with the intertidal ranges described above, although estuaries may be incorrectly classified, or the estimates of intertidal area in the NZCHS inaccurate.

- Most SIDEs have intertidal area >40%. Macroalgae is expected to be the primary producer mostly likely to drive other eutrophic symptoms in SIDEs, and effects of phytoplankton blooms usually localised to deep holes.
- Coastal Lakes are normally closed to the sea and have salinities too low to support estuarine macroalgal blooms. Intertidal area is normally zero, although there may be backwater effects that give the appearance of tidal water level fluctuations, resulting in non-zero estimates of intertidal area in the NZCHS. Phytoplankton is the primary producer of most concern in coastal lakes.
- SSRTREs have a range of intertidal areas, but commonly in the range 5-40%. While many SSRTREs have short residence times which restricts phytoplankton growth, some have deep holes that may become stratified, or partial mouth restrictions increasing residence times; both situations can provide conditions for harmful phytoplankton blooms to occur. SSRTRE may also have intertidal margins, or lagoons attached to the main channel where macroalgae blooms may occur. Usually macroalgae is the primary producer of concern due to short residence times, but both macroalgae and phytoplankton should be considered in SSRTRE.
- DSDEs also have a range of intertidal areas, commonly between 5 and 40%. DSDEs have long residence times, making them susceptible to phytoplankton blooms. Some may also have significant intertidal and shallow areas where macroalgae can become established. Both phytoplankton and macroalgae should be considered in DSDEs.

Note that the ETI susceptibility tools do not make predictions of aquatic macrophyte abundance (we use the term ‘macrophyte’ to refer to aquatic plants visible to the naked eye, excluding all algae). Macrophytes can be the dominant primary producer in freshwater/brackish systems such as coastal lakes and some riverine estuaries. Macrophytes can grow well in comparatively low nutrient environments. However, under high nutrient loads, high phytoplankton concentrations can shade macrophytes, leading to a system ‘flipping’ from macrophyte to phytoplankton dominance. The ETI tools also do not consider benthic microalgae, which can be dominant in tidal estuaries, particularly those with strong currents that scour or detach macroalgae. The response of benthic microalgae to nutrients is likely similar to that of macroalgae, and there is some evidence that the ETI potential TN concentrations developed for macroalgae are also relevant for effects of microalgae (Plew and Dudley 2018b; Plew, Dudley et al. 2020; Zeldis, Depree et al. 2020).

2.4 Coastal nutrient concentrations

Coastal nutrient concentrations are needed for the dilution modelling and to calculate nutrient concentrations within estuaries. The coastal nutrient concentrations should represent offshore values, beyond the plume from the estuary discharge. Coastal nutrient concentrations were compared from two sources: the CSIRO Atlas of Regional Seas (CARS) climatology (CSIRO 2011), and from seasonal (quarterly) shoreline samples reported by Babaranti (2018) from Allans Beach on the Otago Peninsula. CARS gives higher dissolved inorganic nitrogen (DIN) values than those observed at Allans Beach but a similar dissolved reactive phosphorus (DRP) concentration. In previous estuary susceptibility studies, concentrations of 40 mg m^{-3} DIN and 1 mg m^{-3} DRP were used (Plew and Dudley 2018b; Plew and Dudley 2018a; Plew, Dudley et al. 2019a; Plew, Dudley et al. 2019b). Here, we use the annual average concentrations from Allans Beach for macroalgal response (36 mg m^{-3}), and the Allans Beach summer concentrations for phytoplankton (18 mg m^{-3} DIN and 11 mg m^{-3} DRP). For estuaries, our macroalgae and phytoplankton abundance predictions are based on TN and TP rather than DIN or DRP concentrations. In South Island east coast ocean waters, TN and TP can be high compared to DIN and DRP (Dudley, Plew et al. 2019), but the organic nitrogen component of TN and the non-DRP component of TP are mostly in particulate form, including oceanic phytoplankton biomass, and not readily available for uptake by estuary algae. Therefore, coastal DIN and DRP values are used as boundary conditions for the dilution model.

Table 2-5: Comparison of coastal nutrient concentrations from the CARS climatology and at Allans Beach, Otago Peninsula. Observations at Allans Beach are from Babaranti (2018).

Site	Annual DIN (mg m^{-3})	Annual DRP (mg m^{-3})	Summer DIN	Summer DRP
CARS	69	16	53	22
Allans Beach	36	19	18	11

2.5 Estuary nutrient loads

Predictions of current estuary state are made using annual TN and TP loads estimated by Land Water People (LWP) (Snelder 2021), given in Table 3-1. A comparison is made between these load estimates with output from CLUES (Semadeni-Davies, Jones-Todd et al. 2020) based on a 2017 land use layer, in Figure 2-7. LWP predictions of TN are slightly higher than those from CLUES, particularly for catchments with low (<30 t y^{-1}) TN loads. Considering each estuary separately, the LWP TN loads to estuaries average 60% higher than those from CLUES, although accumulated across the Otago region, the total LWP TN load is only 22% higher than that from CLUES. LWP TP loads are on average 14% higher than CLUES loads to individual estuaries, while the accumulated TP load across the Otago region is 18% lower. CLUES has been calibrated using a national water quality dataset, while the LWP model uses data from Otago to reduce regional biases. More details of the load modelling by LWP are given by Snelder (2021).

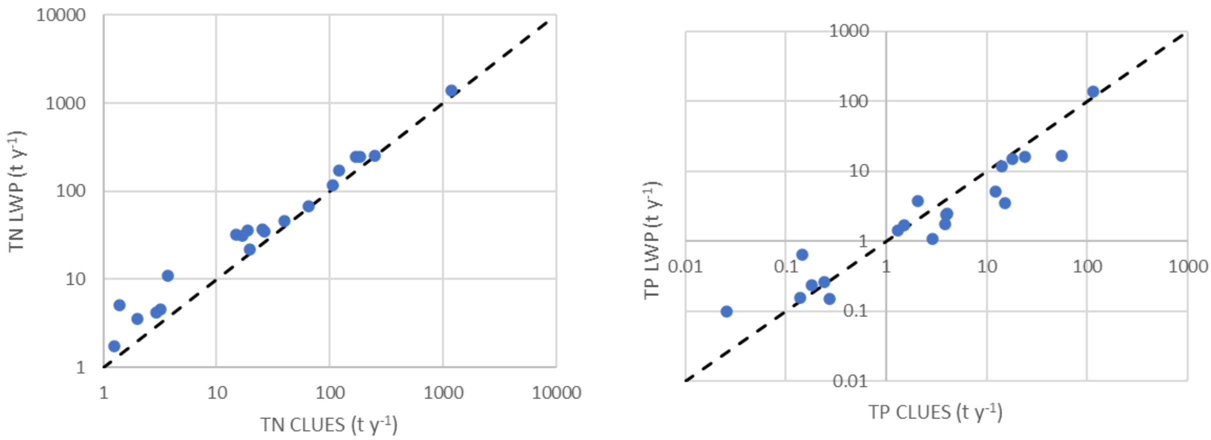

Figure 2-7: Comparison between predicted total nitrogen (TN) and total phosphorus (TP) loads to estuaries provided by LWP with CLUES. CLUES outputs are based on a 2017 land use layer. The dashed line indicates 1:1. Points above the line indicate LWP loads higher than CLUES.

NIWA have previously estimated nutrient loads from observed riverine nutrient concentrations and flows for four of the estuaries. Where the flow and nutrient observations were some distance upstream of the estuaries, loads were scaled based on statistically modelled loads and flows (Booker and Woods 2014) at the samplings sites and estuary upstream margins to account for ungauged parts of the catchments. Table 2-6 compares load predictions from LWP with those previously calculated by NIWA. LWP's method gave higher annual TN and TP loads than estimated by NIWA for most estuaries. The differences can be attributed to the methods used to calculated loads. NIWA values are a 5-year average, multiplying daily river flow by estimated daily nutrient concentration interpolated from monthly samples. LWP calibrated their model using a rating curve between observed flow and river concentrations, with seasonal and long-term trend adjustments applied to the rating curve. Further discussion of the differences in load estimates are given in section 3.1.

Table 2-6: Comparison of modelled estuary nutrient loads with loads from previous NIWA studies. Modelled loads are described by Snelder (2021).

Estuary	Modelled TN (kg y^{-1})	Observed TN (kg y^{-1})	Modelled TP (kg y^{-1})	Observed TP (kg y^{-1})	NIWA reference
Shag River Estuary	118,636	64,600	3,432	Not calculated	Plew and Dudley (2018b)
Kaikorai Estuary	22,075	10,200	1,422	420	Plew, Dudley et al. (2019a)
Tokomairiro Estuary	246,661	77,700	11,849	3,140	Plew, Dudley et al. (2019b)
Pounawea (Catlins) Estuary	248,849	235,600	16,117	Not calculated	Plew and Dudley (2018a)

3 Results

3.1 Predicted estuary state

Nine estuaries have a band D (very high) eutrophication susceptibility based on current load estimates (see Table 3-1).

Kakanui Estuary is known to be an ICOE with frequent and occasionally extended closure periods. It scores a band D for macroalgae when the mouth is open, and band D for phytoplankton when the mouth is closed. Habitat mapping from 2009 noted that macroalgae were generally scarce in the estuary (Steward 2009). However, more recent investigations report extensive mats of *Ulva intestinalis* (Plew and Barr 2015), consistent with a D banding, but the author is not aware of any recent monitoring of macroalgae cover or biomass.

Orere Lagoon, Stoney Creek Lagoon and Tomahawk Lagoon all have very high (band D) eutrophication susceptibilities. These hydrosystems are all classified as beach streams or coastal lakes, and have intermittent, if any, connection with the ocean. Water drains from these lagoons either over or through a beach barrier. Sea water input will be minimal; these systems will be fresh or brackish. Low salinity means that estuarine macroalgae are unlikely to be present, although macrophyte species may be. The very high eutrophication susceptibilities are due to the high potential for phytoplankton blooms, resulting from high nutrient concentrations and long flushing times. Phosphorus is predicted to be the limiting nutrient for phytoplankton in all three systems.

Kaikorai Estuary is also a known ICOE with frequent and occasionally extended closure periods. It is classified as band D with very high susceptibility for both macroalgal and phytoplankton blooms when the mouth is open, and phytoplankton blooms when the mouth is closed. The high intertidal area indicates that macroalgal blooms are likely to be the main concern when the mouth is open, although phytoplankton blooms may be a risk factor in the deeper upper reaches of the estuary (where the Kaikorai Stream enters), and throughout the estuary during mouth closure events. Broadscale monitoring in 2018 found little macroalgae present in the estuary, but noted that prior flood flow may have removed macroalgal cover (Stevens 2018a). Large areas of poorly oxygenated sediment were found (Stevens 2018a), and a previous survey in December 2017 found high macroalgae (*Ulva*) cover and high water column chlorophyll-*a* (Robertson and Robertson 2018). These findings are consistent with the very high susceptibility score. Current TN and TP loads predicted by Snelder (2021) are 2.2× and 3.4× higher than those calculated by Plew, Dudley et al. (2019a). Both load estimates result in the same susceptibility band (D).

Taieri Estuary is classified as band D with very high susceptibility for macroalgal blooms. Taieri River has low intertidal area (~10%) and is a SSRTRE. SSRTRE estuaries commonly tolerate much higher nutrient loads than SIDE estuaries as high velocities and limited suitable habitat can limit macroalgae growth. The potential TN concentration is ~ 3x higher than the band C/D threshold, indicating that some macroalgal growth may be expected, although the extent of blooms may be restricted by suitable habitat and scour. The estimated flushing time of 3.6 days is close to the minimum required to sustain phytoplankton growth (~3.3 days). As Figure 2-5 illustrates, the phytoplankton model is highly sensitive to flushing time values that are close to this minimum value. When the flushing time is slightly higher than this minimum, phytoplankton biomass can accumulate faster than it is exported to the ocean if nutrient concentrations are high. The model suggests that current nutrient concentrations are not sufficient for this to occur. However, the estimated flushing time is determined by flow and volume, both of which are estimated for this estuary. Uncertainty in these values means that phytoplankton blooms are a possibility for the Taieri Estuary, however in this report macroalgae is used to define susceptibility and to estimate load bands.

Tokomairiro Estuary is classified as band D using current loads. As a SSRTRE with a moderate flushing time and intertidal area, Tokomairiro Estuary is sensitive both to macroalgal and phytoplankton blooms. The TN and TP loads calculated by Snelder (2021) are 3.2× and 3.8× than those calculated by Plew, Dudley et al. (2019b) (Table 2-6). Both load estimates result in a very high (band D) susceptibility score for the Tokomairiro Estuary. Broadscale monitoring of this estuary returned an ETI score of 0.59, placing this estuary in a band C (Stevens 2018b). Stevens (2018b) note that this score likely underestimates the extend of eutrophic symptoms as the predominantly subtidal eutrophic upper reaches of the estuary were largely excluded from the ETI scoring assessment. Plew, Dudley et al. (2019b) also constructed a two-compartment dilution model to resolve the upper and lower parts of the estuary. That approach gave a band B (low-moderate) for the lower estuary based on macroalgae, and band D (very high) for the upper estuary due to phytoplankton. While Tokomairio Estuary may be considered an ICOE, mouth closure events appear to be infrequent and of short duration (Plew, Dudley et al. 2019b). Therefore, only the open state is considered here.

Tahakopa Estuary is the other estuary with band D (very high) susceptibility. This estuary has a short flushing time and moderate intertidal area. The ETI susceptibility band is based on the predicted macroalgal response. The predicted potential TN concentration (330 mg m^{-3}) is very close to the C/D band threshold of 320 mg m^{-3} for macroalgae. The estuary type and near-threshold potential TN suggest that field investigations to confirm the ecological state of this estuary would be insightful.

Five estuaries (Pleasant River Estuary, Waikouaiti Estuary, Pounawea (Catlins) Estuary, Tautuku Estuary and Waipati (Chaslands) Estuary) scored C bands for eutrophication susceptibility. All five estuaries are classified as Tidal Lagoons (permanently open) or SIDEs. Macroalgae is the primary producer most likely to drive secondary eutrophic responses including sediment deoxygenation, sediment nutrient enrichment and macrofaunal community changes. There is good agreement between annual nutrient loads provided by LWP and calculated previously by NIWA for Pouanwea (Catlins) Estuary. Plew and Dudley (2018a) developed a two-compartment dilution model which distinguished between the upper estuary (Catlins Lake) and lower estuary. The upper estuary has a high sensitivity to nutrient loads than the more highly flushed lower estuary. The upper estuary is also more sensitive to loads from the Catlins River, while the lower estuary shows similar sensitivity to loads from both the Catlins and Owaka Rivers. An ETI score of 0.62 calculated from broadscale monitoring (Stevens and Robertson 2017a) is consistent with the C band calculated here.

Shag River Estuary, Blueskin Bay and Purakaunui Inlet are also Tidal Lagoons (permanently open), or SIDEs, and all have band B susceptibilities based on the predicted macroalgae response. The LWP calculated TN loads for Shag River Estuary are 1.8× higher than those estimated by NIWA (Table 2-6) , yet both loads result in the same ETI susceptibility band. Broadscale monitoring gave an ETI score of 0.35 (band B), consistent with the susceptibility band, although macroalgal EQR was low at the time of observations, possibly due to recent high flow events (Stevens and Robertson 2017b).

Otago Harbour, Papanui Inlet and Hoopers Inlet all scored band A (low eutrophication risk). Macroalgae is the primary producer of most concern in Papanui Inlet and Hoopers Inlet due to their high portions of intertidal area. Otago Harbour is likely susceptible to both macroalgae and phytoplankton blooms. While the estimated intertidal area is 43% (greater than the 40% threshold used in the ETI to define macroalgal susceptibility), the Harbour is deep (bathymetry charts show the channel is dredged to 13.5 m, and >30 m depth occurs near Goat Island) and has a long flushing time

(~32 days) so phytoplankton should be considered alongside macroalgae. Under current loading, the equivalent ETI score derived from macroalgal EQR is slightly higher than that from the predicted peak phytoplankton chlorophyll-*a* concentration, but both place the Otago Harbour in band A.

Table 3-1: Estuary eutrophication susceptibility bands based on current total nitrogen (TN) and total phosphorus (TP) loads. Annual TN and TP loads provided by LWP. Salinity, summer flushing time and potential TN concentrations are estimated by dilution modelling. Macroalgae EQR and phytoplankton chlorophyll-*a* (Chl-*a*) concentrations are predicted from the dilution model output and assigned to susceptibility bands A-D for macroalgae and phytoplankton, respectively. The limiting nutrient for phytoplankton is indicated as N = nitrogen, P = phosphorus. "Flushing time" indicates the flushing time is too short for phytoplankton to accumulate. The overall ETI susceptibility band is based on either the macroalgal or phytoplankton susceptibility depending on the intertidal area.

Estuary	% intertidal	TN load ($t\ y^{-1}$)	TP load ($t\ y^{-1}$)	Salinity	Potential TN ($mg\ m^{-3}$)	Flushing time (d)	EQR	ETI_M	Chl-*a* ($\mu g\ l^{-1}$)	ETI_P	Limiting nutrient for phytoplankton	Macroalgal susceptibility band	Phytoplankton susceptibility band	Overall ETI score	ETI band
Kakanui Estuary	21.2	252.6	16.43	8.955	963	1.8	0	1.0	0	0.0	flushing time	D	A	1.00	**D**
Kakanui Estuary (closed)				*0*	*1275*	*4.9*	*1*	*0.0*	*68*	*1.0*	*P*	*A*	*D*	*1.00*	***D***
Orore Lagoon	0	10.99	0.6304	0	2954	14.4	1	0.0	139	1.0	P	A	D	1.00	**D**
Shag River Estuary	67.5	118.6	3.432	30.8	192	0.7	0.61	0.48	0	0.0	flushing time	B	A	0.48	**B**
Stony Creek Lagoon	0	5.039	0.1568	0	2582	54	1	0.00	66	1.0	P	A	D	1.00	**D**
Pleasant River Estuary	85.3	31.71	1.062	26	300	5.5	0.43	0.72	13	0.58	P	C	C	0.72	**C**
Waikouaiti Estuary	67.7	68.49	5.168	23.8	258	4.29	0.5	0.62	10	0.40	N	C	B	0.62	**C**
Blueskin Bay	85.8	37.29	1.774	32.2	174	4.5	0.64	0.45	9.8	0.61	N	B	C	0.45	**B**
Purakaunui Inlet	88.2	3.562	0.1481	34	125	12.8	0.72	0.35	6.2	0.39	N	B	B	0.35	**B**
Otago Harbour	45.3	46.52	2.496	34.8	56.9	32.1	0.84	0.20	2.8	0.18	N	A	A	0.20	**A**
Papanui Inlet	59.9	4.223	0.2315	35	72.4	12.9	0.81	0.23	3.0	0.19	N	A	A	0.23	**A**
Hoopers Inlet	94.8	4.529	0.2635	34.9	74.5	11.7	0.81	0.24	2.9	0.18	N	A	A	0.24	**A**
Tomahawk Lagoon	1.7	1.722	0.1002	0	8846	70.2	1	0.00	424	1.0	P	A	D	1.00	**D**
Kaikorai Estuary	97	22.08	1.4215	20.4	610	7.4	0	1.00	41	0.95	P	D	D	1.00	**D**
Kaikorai Estuary (closed)				*0*	*1390*	*33*	*1*	*0.0*	*73*	*1.0*	*P*	*A*	*D*	*1.00*	***D***
Taieri River	10	1410	138.9	13.1	633	3.6	0	1.00	0	0.00	flushing time	D	A	1.00	**D**
Akatore Estuary	74.9	31.82	1.666	23.7	506	2.7	0.09	1.00	0	0.00	flushing time	D	A	1.00	**D**
Tokomairiro River	23	246.7	11.85	19.3	1618	6.8	0	1.00	76	1.00	P	D	D	1.00	**D**

Estuary	% intertidal	TN load (t y^{-1})	TP load (t y^{-1})	Salinity	Potential TN (mg m^{-3})	Flushing time (d)	EQR	ETI_M	Chl-*a* (µg l^{-1})	ETI_P	Limiting nutrient for phytoplankton	Macroalgal susceptibility band	Phytoplankton susceptibility band	Overall ETI score	ETI band
Pounawea (Catlins) Estuary	73.1	248.8	16.12	29.1	233	5.3	0.54	0.57	11	0.47	N	C	B	0.57	**C**
Tahakopa Estuary	30.9	171.9	14.96	21.1	330	1.8	0.38	0.77	0	0.0	flushing time	D	A	0.77	**D**
Tautuku Estuary	61.5	35.80	3.765	24.7	285	5.1	0.46	0.68	19	0.78	N	C	D	0.68	**C**
Waipati Estuary	79.8	34.86	2.377	22.5	269	2.1	0.48	0.64	0	0.0	Flushing time	C	A	0.64	**C**

3.2 Estuary nutrient load bands

Annual nutrient loads corresponding to thresholds between ETI susceptibility bands of A, B, C and D have been calculated for macroalgae and phytoplankton for each estuary (Table 3-2). Only TN loads are calculated for macroalgae response because TP concentration thresholds have not been established for macroalgae. Macroalgae are seldom phosphorus limited in New Zealand estuaries (Barr 2007; Robertson and Savage 2018; Plew, Zeldis et al. 2020) because they have low phosphorus requirements (Atkinson and Smith 1983; Dudley, Barr et al. submitted). In estuaries where salinity is too low to support estuarine macroalgal growth, no TN load band thresholds can be calculated, and these are marked as n/a in Table 3-2.

Estuarine phytoplankton may be limited by either nitrogen or phosphorus (Plew, Zeldis et al. 2020). The phytoplankton model includes both nitrogen and phosphorus, and load bands were calculated for both TP and TN independently by setting one of these to a very high, non-limiting value, and perturbating the other value to obtain the response in modelled chlorophyll-*a* concentration. Modelled chlorophyll-*a* and nutrient loads follow a linear response, so load thresholds corresponding to the chlorophyll-*a* band thresholds given in Table 2-4 could be calculated by linear interpolation. For some estuaries, the lowest bands (A and/or B) cannot be obtained by lowering TP loads (a negative TP load would be required) because sufficient phosphorus is supplied by the ocean. These cases are marked as n/a in Table 3-2. Note that to obtain a desired phytoplankton band, it would only be necessary for one of either the TN or TP loads to be below the band threshold. For example, if TN loads indicate a B band but TP loads indicate a band D, then the appropriate phytoplankton band is B, and nitrogen would be the limiting nutrient.

Some estuaries have flushing times too short to support phytoplankton growth, according to the model, so TN and TP loads cannot be calculated, and the corresponding entries in Table 3-2 are marked by a dash (-).

The recommended nutrient load thresholds (Table 3-2) are based on either the macroalgal or phytoplankton bands as appropriate for each estuary. For estuaries where macroalgae is the primary producer that is most likely to lead to adverse ecological impacts, and where effects of phytoplankton blooms are likely mitigated by the estuaries being shallow and well-mixed, only nitrogen load band thresholds are given. No phosphorus load band thresholds can be calculated for macroalgae, and because there is greater uncertainty in our ability to predict phytoplankton blooms ((Plew, Zeldis et al. 2020)) it is not appropriate to set phosphorus load limits for these estuaries.

For estuaries where phytoplankton blooms are considered problematic (and where macroalgae growth likely inhibited by low salinities), the recommended load bands are based on the phytoplankton bands, and are given for both TN and P.

For Otago Harbour, the load thresholds for phytoplankton are used as these are lower than those for macroalgae. Otago Harbour is a DSDE with long flushing time, therefore phytoplankton blooms are a risk factor, while macroalgae blooms may be of concern in shallow or intertidal areas.

For the two ICOEs Kakanui Estuary and Kaikorai Estuary, TN bands are based on those for macroalgae, derived for the open state, while TP bands are those derived for phytoplankton for the closed state. The reasoning for this is that these ICOEs are normally open, and in their open state, managing for macroalgae is of more importance than for phytoplankton. Phytoplankton blooms may occur when these systems close for long periods (more than 1 week). The B/C and C/D TN band thresholds for phytoplankton are more restrictive than those for macroalgae and applying these may be unnecessarily restrictive for the normal, open estuary state. When closed, phosphorus has been identified as likely to be the limiting nutrient for phytoplankton growth in these estuaries (Table 3-1), consequently smaller load reductions would be required for phosphorus than nitrogen if managing for phytoplankton blooms is desired.

Table 3-2: Nutrient load thresholds ($t\ y^{-1}$) corresponding to ETI susceptibility band thresholds. Load thresholds are calculated separately for macroalgae and phytoplankton. Overall load thresholds are based on the load band appropriate for each estuary type. n/a indicates no macroalgae load threshold can be calculated due to low salinity, or if the phytoplankton band threshold cannot be obtained due to ocean nutrient concentrations. Dashes (-) in the phytoplankton thresholds are where the estuary flushing time is too short to support phytoplankton. Dashes in columns for recommend load thresholds for TP indicate where it is not considered appropriate to apply TP load bands. Recommended TP bands for Kakanui Estuary and Kaikorai Estuary are based on their closed state while TN bands are based on the open state.

Estuary	Macroalgae band			Phytoplankton band						Determining Band	Recommended load thresholds					
	TN (t/y)			TN (t/y)			TP (t/y)				TN (t/y)			TP (t/y)		
	A/B	B/C	C/D	A/B	B/C	C/D	A/B	B/C	C/D		A/B	B/C	C/D	A/B	B/C	C/D
Kakanui Estuary	**18.8**	**50.6**	**82.4**	-	-	-	-	-	-	Macroalgae (phytoplankton if closed)	18.8	50.6	82.4	2.0	2.9	3.9
Kakanui Estuary (closed)	*n/a*	*n/a*	*n/a*	*28.9*	*35.9*	*42.8*	*2.0*	*2.9*	*3.9*	*Phytoplankton*						
Orore Lagoon	n/a	n/a	n/a	**0.37**	**0.86**	**2.0**	**0.04**	**0.11**	**0.27**	Phytoplankton	0.37	0.86	2.0	0.04	0.11	0.27
Shag River Estuary	**36.0**	**125**	**213**	-	-	-	-	-	-	Macroalgae	36	125	213	-	-	-
Stony Creek Lagoon	n/a	n/a	n/a	**0.18**	**0.43**	**1.04**	**0.024**	**0.06**	**0.14**	Phytoplankton	0.18	0.43	1.04	0.024	0.06	0.14
Pleasant River Estuary	**6.1**	**19.8**	**33.5**	15.2	20.1	25.0	0.18	0.86	1.5	Macroalgae	6.1	19.8	33.5	-	-	-
Waikouaiti Estuary	**16.4**	**51.5**	**86.6**	61.3	73.4	85.4	0.74	2.4	4.1	Macroalgae	16.4	51.5	86.6	-	-	-
Blueskin Bay	**12.5**	**44.2**	**75.9**	30.1	45.9	61.7	n/a	1.9	4.1	Macroalgae	12.5	44.2	75.9	-	-	-
Purakaunui Inlet	**1.8**	**6.5**	**11.2**	4.7	7.3	9.9	n/a	0.28	0.63	Macroalgae	1.8	6.5	11.2	-	-	-
Otago Harbour	96.4	355	614	**90.4**	**239**	**387**	**n/a**	**n/a**	**15.6**	Phytoplankton	90.4	239	387	n/a	n/a	15.6
Papanui Inlet	**5.1**	**18.8**	**32.5**	13.1	20.2	27.3	n/a	0.75	1.7	Macroalgae	5.1	18.8	32.5	-	-	-
Hoopers Inlet	**5.2**	**19.1**	**33.0**	13.7	20.9	28.2	n/a	0.77	1.8	Macroalgae	5.2	19.1	33.0	-	-	-
Tomahawk Lagoon	n/a	n/a	n/a	**0.02**	**0.04**	**0.10**	**0.002**	**0.006**	**0.014**	Phytoplankton	0.02	0.04	0.10	0.002	0.006	0.014
Kaikorai Estuary	**2.2**	**6.7**	**11.2**	2.9	4.0	5.1	0.14	0.29	0.45	Macroalgae (phytoplankton if closed)	2.2	6.7	11.2	n/a	0.17	0.35
Kaikorai Estuary (closed)	*n/a*	*n/a*	*n/a*	*1.2*	*1.7*	*2.3*	***n/a***	***0.17***	***0.35***	*Phytoplankton*						
Taieri Estuary	**152**	**425**	**698**	-	-	-	-	-	-	Macroalgae	152	425	698	-	-	-
Akatore Creek	**3.7**	**11.6**	**19.5**	-	-	-	-	-	-	Macroalgae	3.7	11.6	19.5	-	-	-
Tokomairiro Estuary	**9.3**	**27.8**	**46.3**	13.0	17.8	22.6	0.6	1.3	1.9	Macroalgae	9.3	27.8	46.3	-	-	-
Pounawea (Catlins) Estuary	**61.7**	**208**	**355**	196	256	317	0.55	8.9	17.3	Macroalgae	61.7	208	355	-	-	-
Tahakopa Estuary	**32.7**	**99.5**	**166**	-	-	-	-	-	-	Macroalgae	32.7	99.5	166	-	-	-
Tautuku Estuary	**7.6**	**24.1**	**40.6**	19.5	25.2	30.8	0.28	1.1	1.8	Macroalgae	7.6	24.1	40.6	-	-	-
Waipati (Chaslands) Estuary	**8.1**	**25.1**	**42.0**	-	-	-	-	-	-	Macroalgae	8.1	25.1	42.0	-	-	-

4 Load band uncertainties

There are uncertainties associated with the nutrient load thresholds proposed in Table 3-2. These uncertainties arise from several sources and cannot be easily quantified. Here, the sources of uncertainty are discussed, and an approach by which a confidence interval for the proposed load bands could be estimated is outlined.

4.1 ETI band thresholds uncertainty

Potential TN band thresholds for macroalgal susceptibility were derived from a regression fit between observed macroalgal EQR and potential TN (Figure 2-4). As Table 4-1 illustrates, there is scatter about the regression fit. This scatter can be attributed to:

- uncertainty in estimation of annual loads used to calculate potential TN concentrations
- uncertainty in estimates of estuary dilution characteristics where salinity data were not available to calibrate dilution models
- variations in seasonal nutrient loading patterns (EQR measurements are made in summer, whilst potential TN concentrations are made from annual loads)
- factors other than nutrient availability restricting macroalgal abundance at the time of survey (e.g., recent floods or scour events, lack of suitable substrate).

The 95% confidence interval for the regression fit can be used to estimate the uncertainty associated with the potential TN concentrations corresponding to EQR values of 0.8, 0.6 and 0.4, which are the macroalgal band A/B, B/C and C/D thresholds respectively. While Figure 2-4 shows the 95% confidence interval for the regression where EQR is the dependant variable, Table 4-1 gives a 95% confidence interval calculated from the regression where potential TN is the dependant variable. This gives a symmetric confidence interval around the potential concentration thresholds associated with each EQR threshold.

Table 4-1: EQR and potential TN concentrations corresponding to ETI macroalgae susceptibility band thresholds. Potential TN concentrations thresholds are rounded off from 82, 202 and 321 mg m^{-3} for bands A/B, B/C and C/D respectively. The 95% confidence intervals are calculated from the regression fit between observed EQR and potential TN (see Figure 2-4).

Threshold	EQR	Potential TN (mg m^{-3})	TN 95% confidence interval (mg m^{-3})
A/B	0.80	80	52 – 112
B/C	0.60	200	171 – 233
C/D	0.40	320	273 – 369

4.2 Tuning factor uncertainty

A 95% confidence interval can also be calculated for the regression-derived predictor of the tuning factor. Figure 4-1 shows both the 95% confidence interval for the regression fit. The 95% confidence interval for the regression is ±0.05.

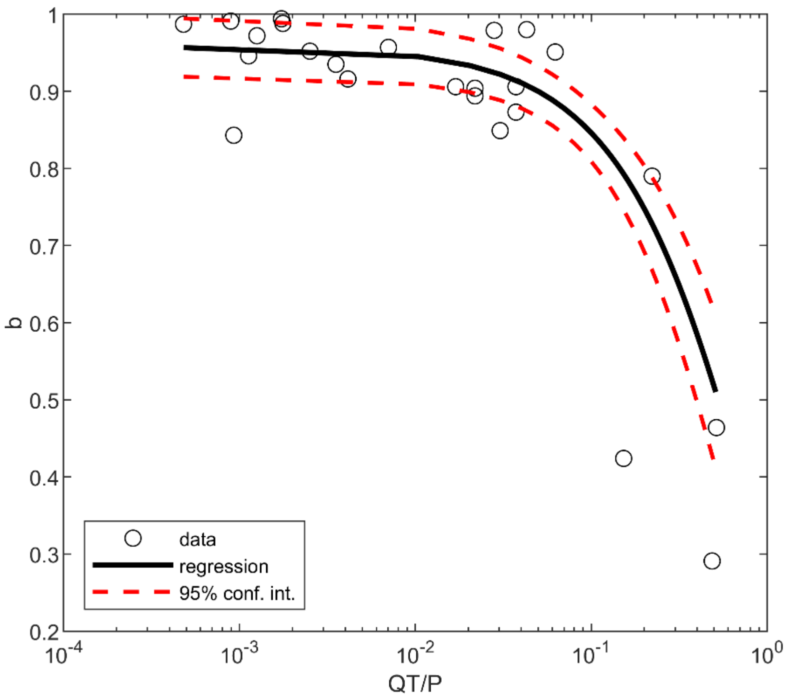

Figure 4-1: Regression of dilution model tuning factor vs ratio of freshwater inflow over a tidal period to the tidal prism. The dashed red lines show a 95% confidence interval for the regression fit.

4.3 Freshwater inflow and tidal prism uncertainty

While the tidal prism has been measured in five of the Otago estuaries (Kakanui Estuary, Shag River Estuary, Kaikorai Estuary, Tokomairiro Estuary and Pounawea (Catlins) Estuary), values from Coastal Explorer (Hume, Snelder et al. 2007) or the NZCHS database (Hume, Gerbeaux et al. 2016) have been used for the other Otago coastal hydrosystems. The Coastal Explorer/NZCHS estimates of tidal prism are compared with recent survey data in Table 4-2. Differences between surveyed data and Coastal Explorer values can be large. In particular, the surveyed tidal prism for Kaikorai Estuary was 295,525 m^3 (Plew, Dudley et al. 2019a), which is only 30% of the 1,001,228 m^3 from Coastal Explorer (a 71% error). Tidal prism may vary over time with estuary morphology changes, and with change in the width and depth of an estuary mouth. The tidal prisms from Coastal Explorer/NZCHS are estimated using a trapezoidal formula (the average of surface areas at high and low tide is multiplied by the tidal range at coast). Actual tidal ranges within an estuary are commonly less than those at the coast (reducing tidal prism), and applying the trapezoid rule also assumes that the wetted area varies linearly with water level. Both approximations can result in errors in tidal prism. Assuming that the Kaikorai Estuary is an outlier, the root-mean-squared-error (rmse) for the remaining four estuaries is 26% of the estimated tidal prisms.

Table 4-2: Comparison of tidal prism from the Coastal Explorer or NZCHS database with surveyed tidal prism.

Hydrosystem name	Coastal Explorer/NZCHS tidal prism (m^3)	Surveyed tidal prism (m^3)	Relative error
Kakanui Estuary	308,411	246,057	+20%
Shag River Estuary	796,648	1,117,500	-40%
Tokomairiro Estuary	765,229	760,000	+1%
Pounawea (Catlins) Estuary	9,328,222	11,763,600	-26%
Kaikorai Estuary	1,001,228	293,525	+71%
Root-mean-squared-error (excluding Kaikorai)			**26%**

Mean annual river flow is used in the dilution model to calculate macroalgal susceptibility. These values are sourced from statistical models calibrated to flow data (Booker and Woods 2014). An estimate of the error in mean annual flow to estuaries is not readily obtained, nor is the interannual variability in mean flow, both of which may influence the appropriate flow to be used in susceptibility assessments. For illustrative purposes, here it is assumed that the uncertainty in flow estimates are normally distributed with a standard deviation of 20% of the mean value.

4.4 Potential TN concentration

The uncertainty in potential TN concentration for an estuary can be estimated by perturbating the freshwater inflow Q, tidal prism P and tuning factor b while calculating the potential TN concentration following the equations in section 2.3.1. Here, each of these parameters is assumed to be normally distributed with standard deviations of Q, P and b estimated as 20%, 26% and 0.025 respectively. Figure 4-2 shows how perturbating each of these inputs separately, and combined, influences the resulting potential TN concentration, using Pleasant River Estuary as an example, for an annual TN load of 10 t y^{-1}. The resulting probability distributions are similar, although slightly greater spreads in the distributions can be seen when perturbating tidal prism and tuning factor compared to flow. Also plotted are the probability distributions associated with the potential TN thresholds between bands A/B, B/C and C/D. For this example, the predicted TN concentration likely exceed the A/B threshold but is below the B/C and C/D thresholds.

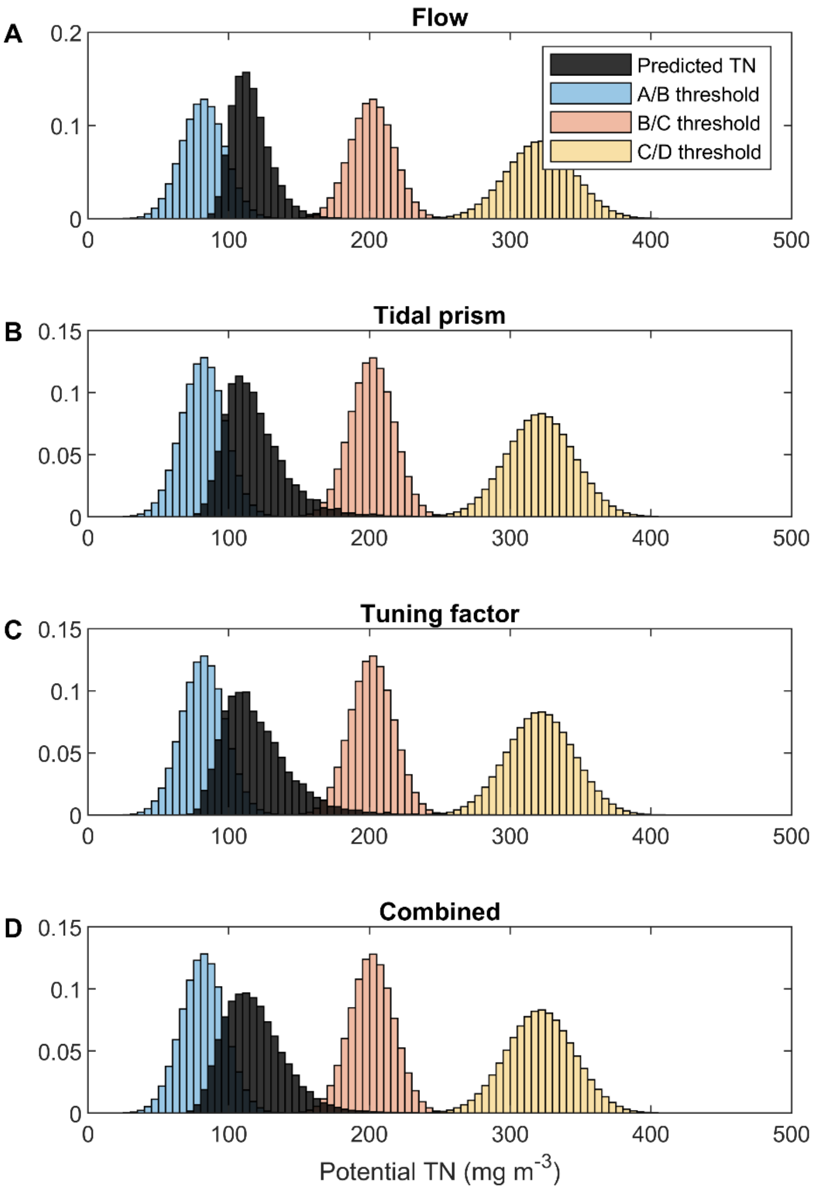

Figure 4-2: Example probability distributions for the potential TN concentrations comparing the effect of varying (A) flow, (B) tidal prism, (C) tuning factor and (D) all three. Calculations are for Pleasant River Estuary with an annual load of 10 t y^{-1} TN. Also shown are the probability distributions associated with the potential TN thresholds between macroalgal bands A/B, B/C and C/D. Flow, tidal prism and tuning factor are assumed to have normal distributions about their mean values with standard deviations of 20%, 26% and 0.025 respectively.

The probability that the predicted potential TN concentration exceeds each band threshold can be calculated assuming that the distribution of both are normally distributed. By repeating this across a range of annual TN loads, exceedance probability curves can be generated for each band threshold. For example, Figure 4-3 shows the exceedance probability curves for Pleasant River Estuary. The curves show the probabilities, as a function of annual TN load, that the potential TN concentration is above the threshold for macroalgal susceptibility bands B, C and D. Figure 4-3 also gives the annual loads at which the exceedance probability is 5%, 50% or 95%. The 50th percentile loads are close the values given in Table 3-2. The small differences are attributable to limits placed on the tunning factor *b* and the freshwater fraction to prevent non-physical results (such as negative values) which subtlety alter the shape of the potential TN distributions, and because the potential TN distributions are not precisely normally distributed (Figure 4-2D shows that the potential TN distributions may be slightly skewed). Annual TN loads corresponding to the 5% and 95% can be considered as indicating the 90% confidence interval for that macroalgal susceptibility band. For this example, if the assumed uncertainties in tidal prism, freshwater inflow and tuning factor are reasonable, then the 90% confidence for the minimum annual TN load required to stay below the band D threshold is 24.4 to 46.8 t y^{-1}.

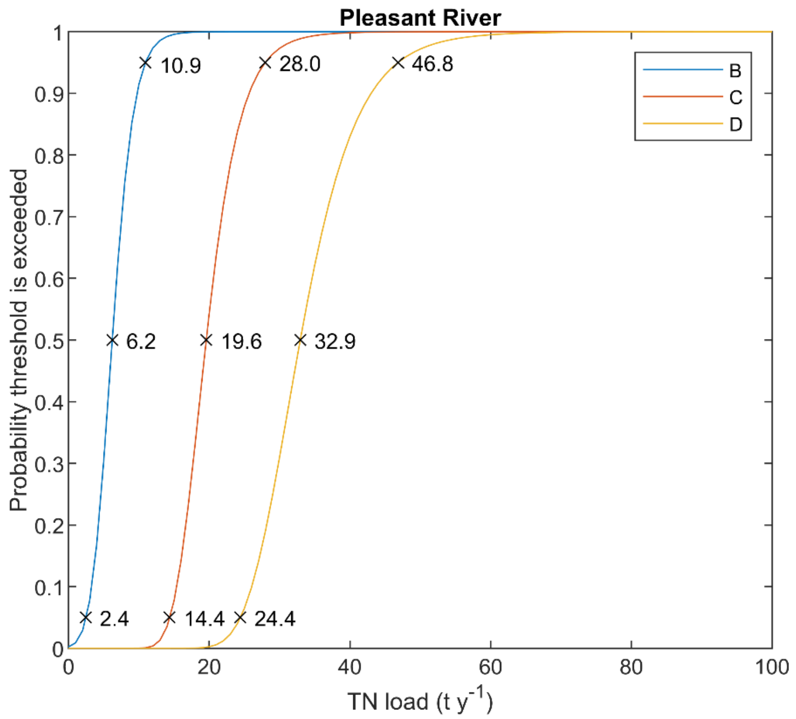

Figure 4-3: Exceedance probability curves for macroalgal susceptibility for Pleasant River Estuary. Points on each curve show the annual TN loads at which there is a 5%, 50% or 95% probability that the macroalgal susceptibility is within or exceeds bands B, C and D.

This method has been applied to the 17 estuaries where macroalgal susceptibility can be calculated. For estuaries where tidal prism has been calculated from surveys, a standard deviation of 5% is used to estimate uncertainty in the tidal prism term. The approximate exceedance probabilities are given in Table 4-3. Based on the assumed uncertainty in tidal prism, freshwater inflow and tuning factor, the 90% confidence interval for loads corresponding to macroalgae band thresholds are approximately -30% to +60% of the mean values.

Table 4-3: Estimated annual TN loads (t y^{-1}) required to exceed macroalgal band thresholds with exceedance probabilities of 5%, 50% and 95% . The spread between loads for the 5% and 95% exceedance probabilities is indicative of the confidence intervals for macroalgal susceptibility load band thresholds. These values are indicative only, and are based on assumed uncertainties in tidal prism, freshwater inflow and dilution model tuning factor.

Estuary	Band A/B			Band B/C			Band C/D		
	5%	50%	95%	5%	50%	95%	5%	50%	95%
Kakanui Estuary	11.3	18.9	28.4	38.9	50.0	65.4	64.0	81.1	105
Shag River Estuary	14.4	31.2	48.6	91.8	111	131	161	190	222
Pleasant River Estuary	3.2	6.3	10.5	14.7	19.9	28.4	25.1	33.5	47.6
Waikouaiti Estuary	8.6	16.3	27.0	36.8	49.9	72.3	62.2	83.6	121
Blueskin Bay	5.9	12.5	22.6	30.1	42.6	67.9	51.7	72.8	116
Purakaunui Inlet	0.8	1.8	3.3	4.4	6.3	10.1	7.6	10.7	17.4
Otago Harbour	40.9	96.2	211	222	343	679	385	590	1170
Papanui Inlet	2.0	4.9	11.8	10.8	17.4	38.9	18.8	29.9	66.8
Hoopers Inlet	2.1	4.9	12.0	11.0	17.6	39.3	19.1	30.3	67.6
Kaikorai Estuary	1.2	2.2	4.0	4.6	6.6	10.9	7.6	10.9	18.1
Taieri Estuary	89.5	149	235	302	405	587	493	661	961
Akatore Estuary	1.9	3.6	6.5	7.7	11.0	18.1	13.0	18.5	30.2
Tokomairiro Estuary	4.8	9.1	18.8	17.5	26.6	51.9	29.0	44.1	86.1
Pounawea (Catlins) Estuary	32.0	63.8	98.8	167	210	263	288	355	442
Tahakopa Estuary	17.8	32.0	51.9	70.7	95.2	136	118	158	226
Tautuku Estuary	4.4	8.5	14.2	20.0	27.0	38.9	33.8	45.4	65.3
Waipati Estuary	4.1	7.8	13.3	16.9	23.5	35.7	28.5	39.2	59.4

In principle, a similar approach could be applied to estimate uncertainty in TN and TP bands for phytoplankton. A Monte Carlo approach could be used to estimate the mean and distribution in phytoplankton concentrations corresponding to different nutrient loads. However, there are many parameters in the phytoplankton model for which uncertainties would need to be estimated. Furthermore, the phytoplankton model is largely unvalidated due to a lack of appropriate water column chlorophyll-*a* data from New Zealand estuaries. There is insufficient information available to estimate appropriate uncertainty bands for the model parameters, so no attempt has been made to estimate TN and TP load band uncertainties for phytoplankton susceptibility.

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Appendix A Otago estuaries and coastal hydrosystems

Figure A-1: Kakanui Estuary. The Kakanui Estuary is classified as a Tidal River Mouth (spit enclosed). It is also an ICOE, closing during periods of low flow. Tidal prism, volume, and area have been calculated from a bathymetry survey conducted by NIWA in 2015. The estuary extents shown are from Coastal Explorer and are consistent with the 2015 survey.

Figure A-2: Orere Lagoon. Orere Lagoon is classified as a Beach Stream (stream with pond). While satellite imagery shows that the lagoon changes in size and shape over time, water drains over or through the beach barrier with little or no sea water input. The extent of the lagoon shown are from Coastal Explorer.

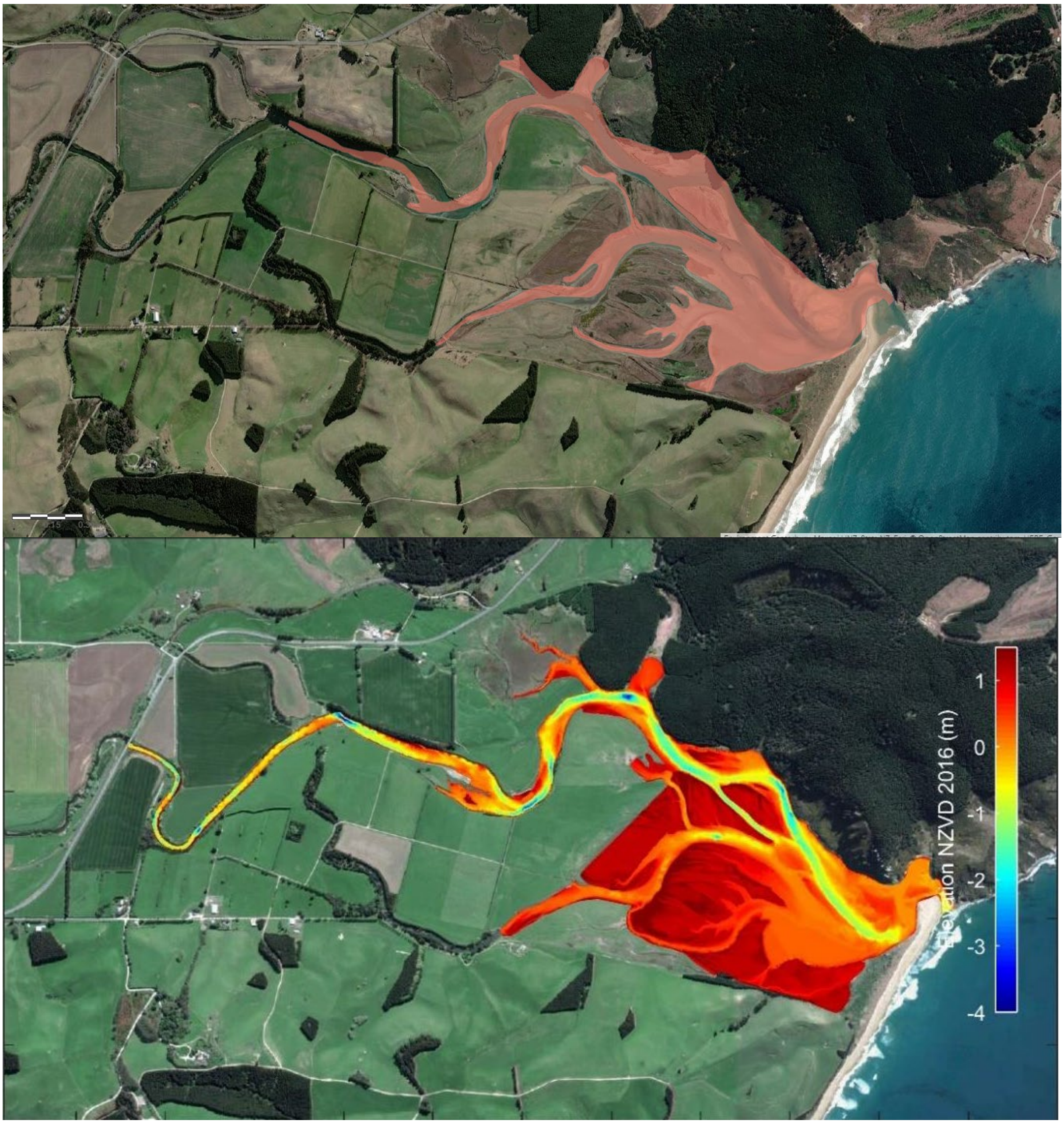

Figure A-3: Shag River Estuary (upper) extents from Coastal Explorer, and (lower) bathymetry surveyed in 2018. Shag River Estuary is classified as a Tidal Lagoon (permanently open). The estuary was surveyed by NIWA in 2018, where saline influence was detected as far upstream as the state-highway bridge. The results of that survey are used to define areas, volume and tidal prism in this study.

Figure A-4: Stoney Creek Lagoon. Stoney Creek Lagoon is classified as a Beach Stream with pond. While Coastal Explorer gives a tidal prism that is nearly 90% of the high tide volume, satellite imagery shows that Stoney Creek has intermittent connection with the ocean, and water flows out either through or over the beach barrier. It appears sea water input will be minimal, and it is modelled here as a coastal lake with 0 tidal prism.

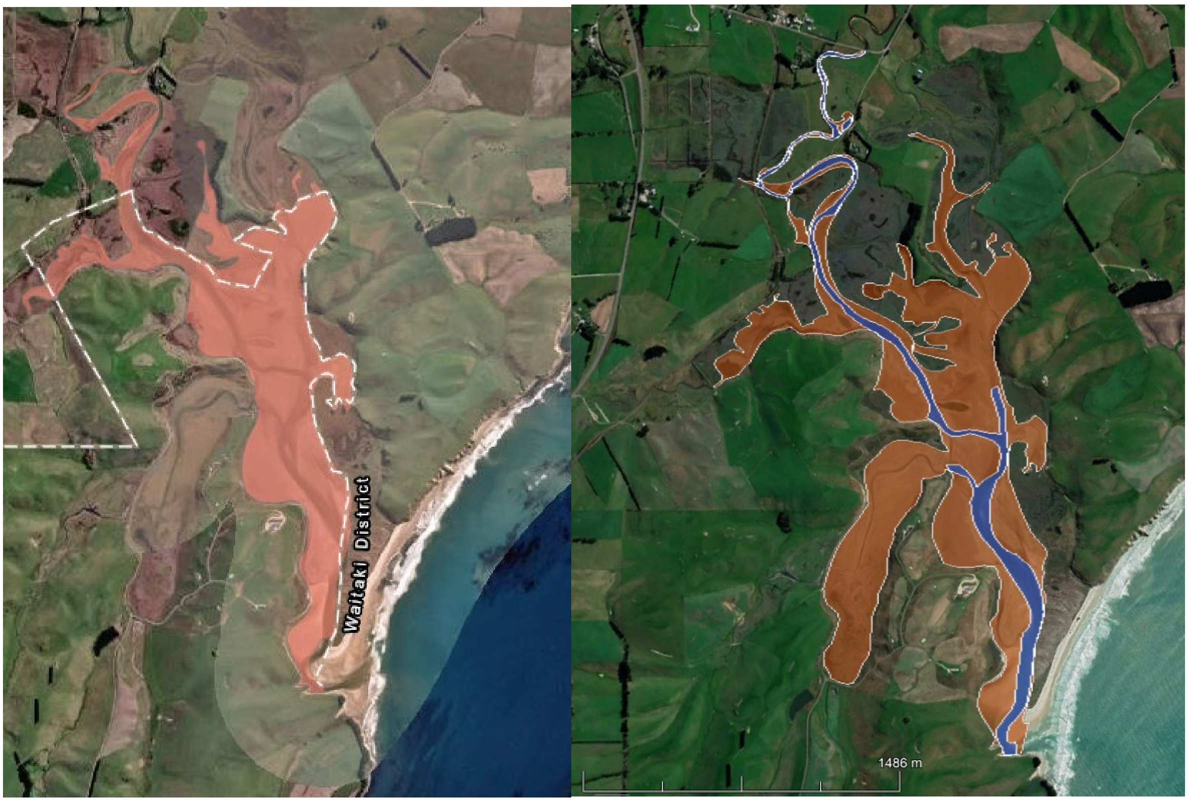

Figure A-5: Pleasant River Estuary extents from Coastal Explorer (left) and re-measured from satellite images. Classified as a tidal lagoon (permanently open). The high and low tide areas were re-measured from satellite images dated 6 July 2019 and 27 February 2018 to include the western arm.

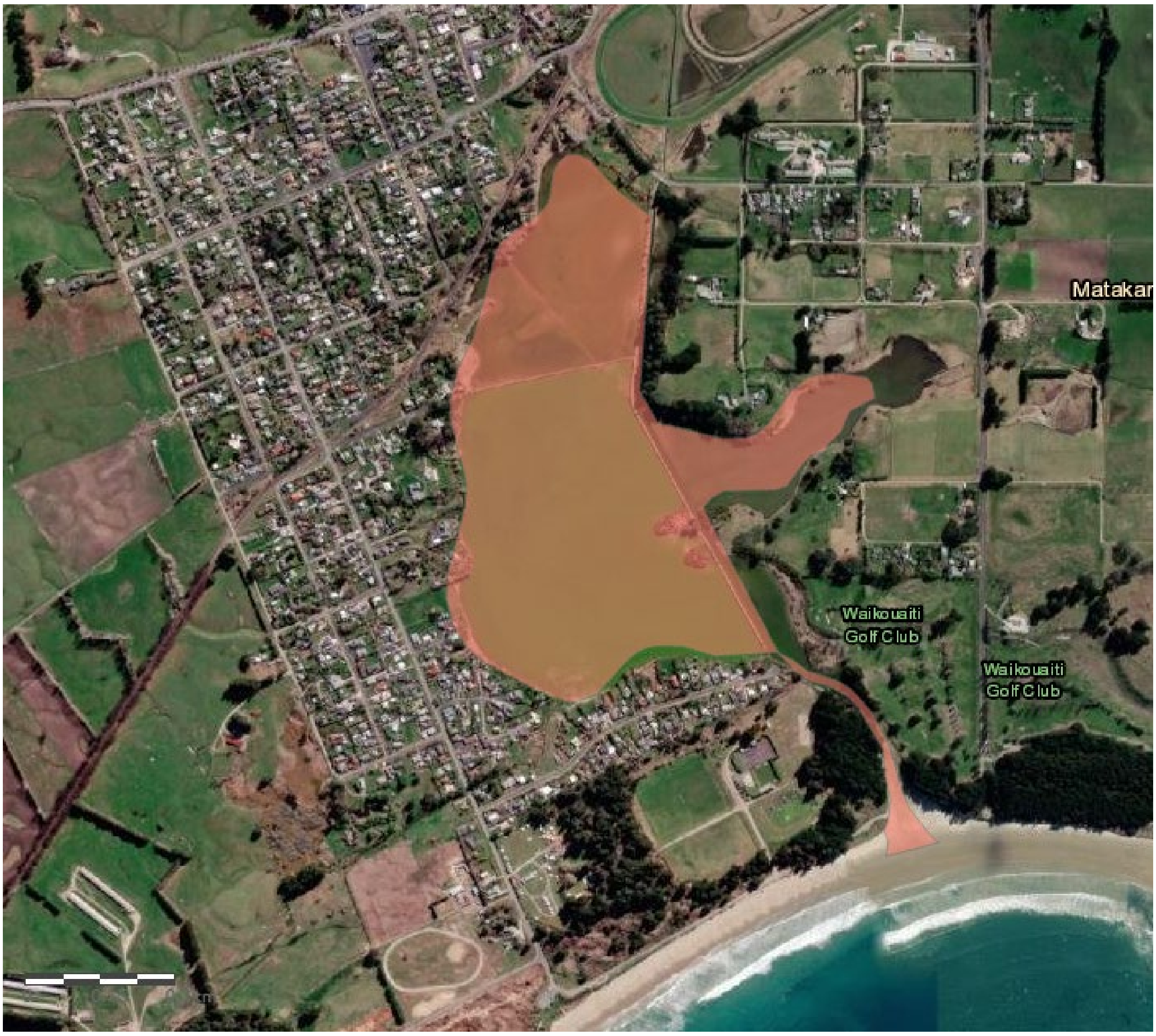

Figure A-6: Waikoauiti (Hawkesbury) Lagoon. Hawkesbury Lagoon is classified as a Beach Stream (damp sand plain lake) or coastal lake. The lagoon is segmented by causeways that will strongly influence circulation patterns and flushing, and the effect of these cannot be incorporated in single compartment models.

Figure A-7: Waikaouiti Estuary. The Waikaouiti Estuary is a Tidal Lagoon (permanently open). Estuary extents shown are from Coastal Explorer.

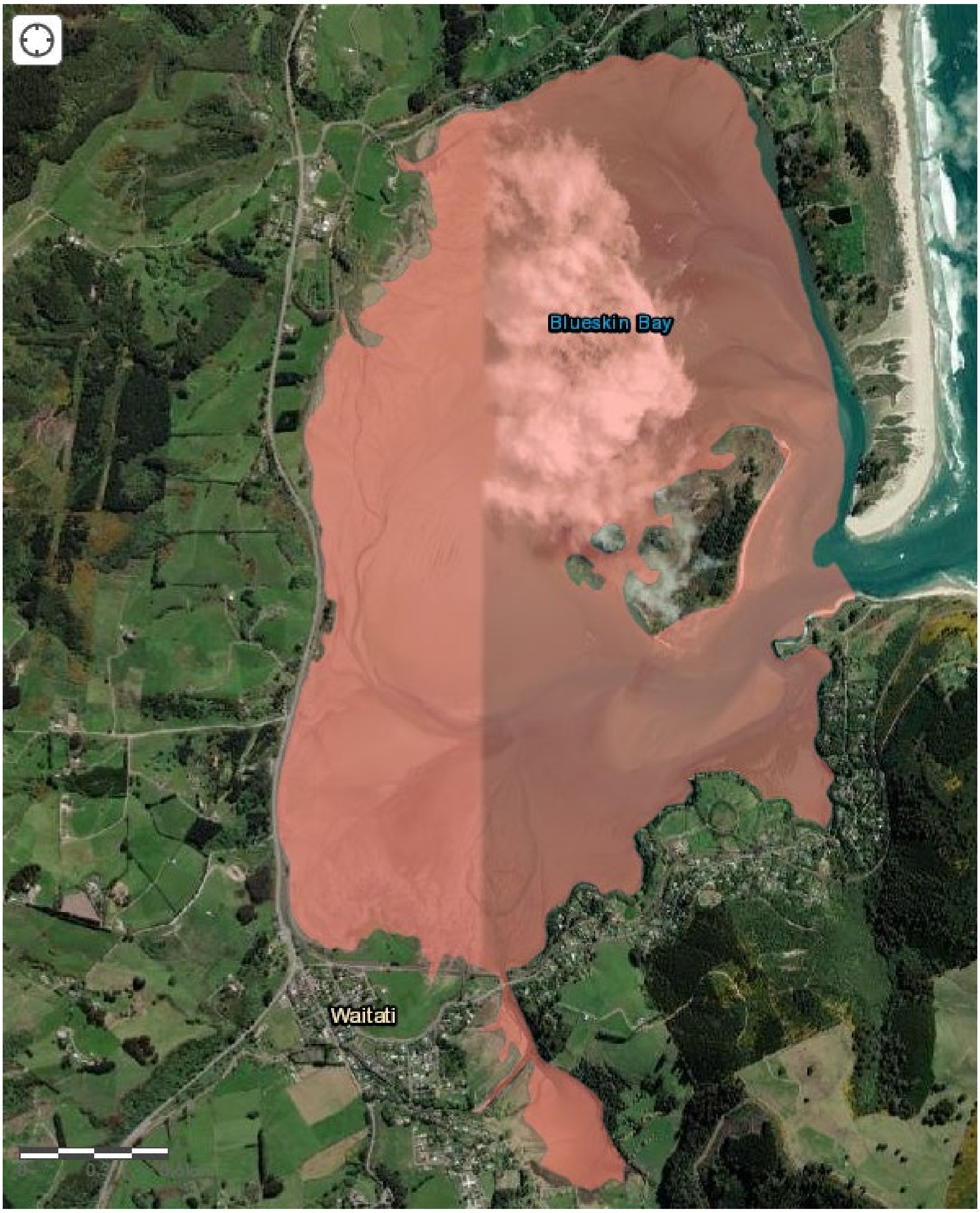

Figure A-8: Blueskin Bay. Blueskin Bay is a Tidal Lagoon (permanently open). Estuary extends shown are from Coastal Explorer.

Figure A-9: Purakaunui Inlet. Purakaunui Inlet is a Tidal lagoon (permanently open). Estuary extents shown are from Coastal Explorer.

Figure A-10: Otago Harbour, Papanui Inlet and Hoopers Inlet. Otago Harbour is a Deep drowned valley. Papanui Inlet and Hoopers Inlet are both Tidal lagoons (permanently open). Estuary extents are from Coastal Explorer.

Figure A-11: Tomahawk Lagoon. Tomahawk Lagoon is classified as a Beach Stream (damp sand plain stream) and is normally closed to the sea. The Coastal Explorer shape file shown excludes the eastern lake.

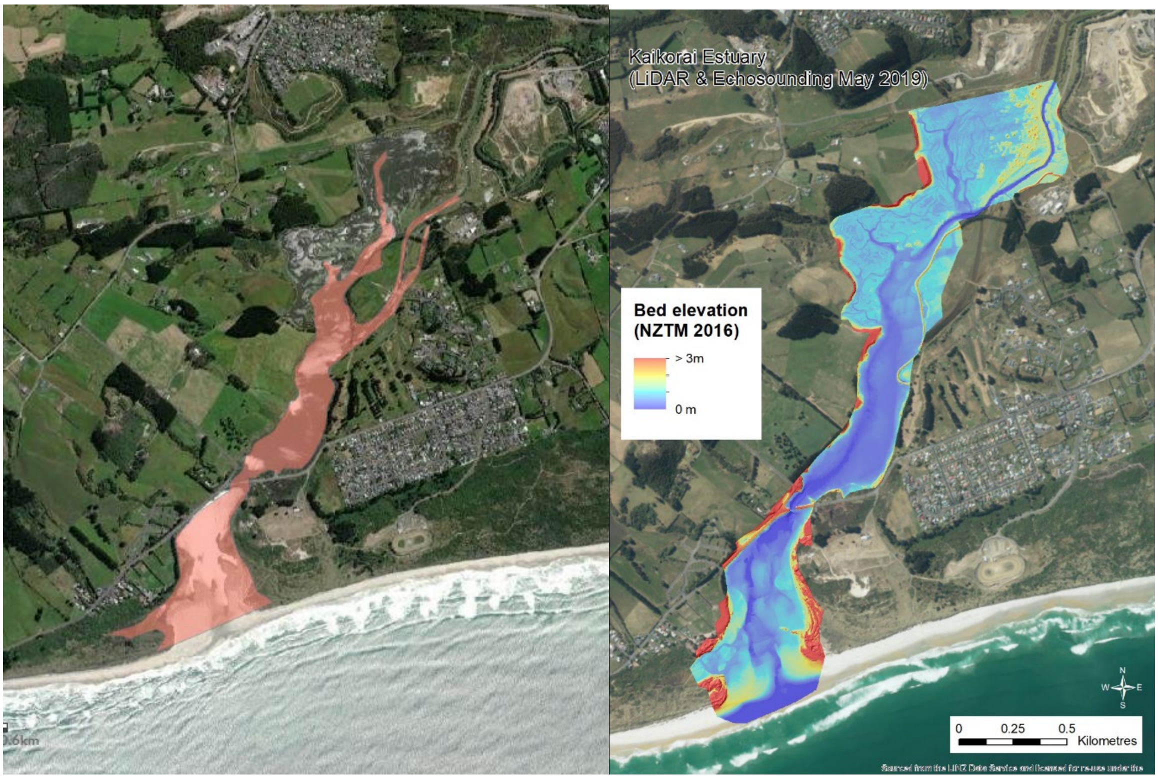

Figure A-12: Kaikorai Estuary extents from (left) Coastal Explorer and (right) bathymetry from a 2019 survey. Tidal prisms, volumes and surface areas used in this study are based on the survey conducted by NIWA in 2019.

Figure A-13: Taireri Estuary. The estuary extents shown are from Coastal Explorer.

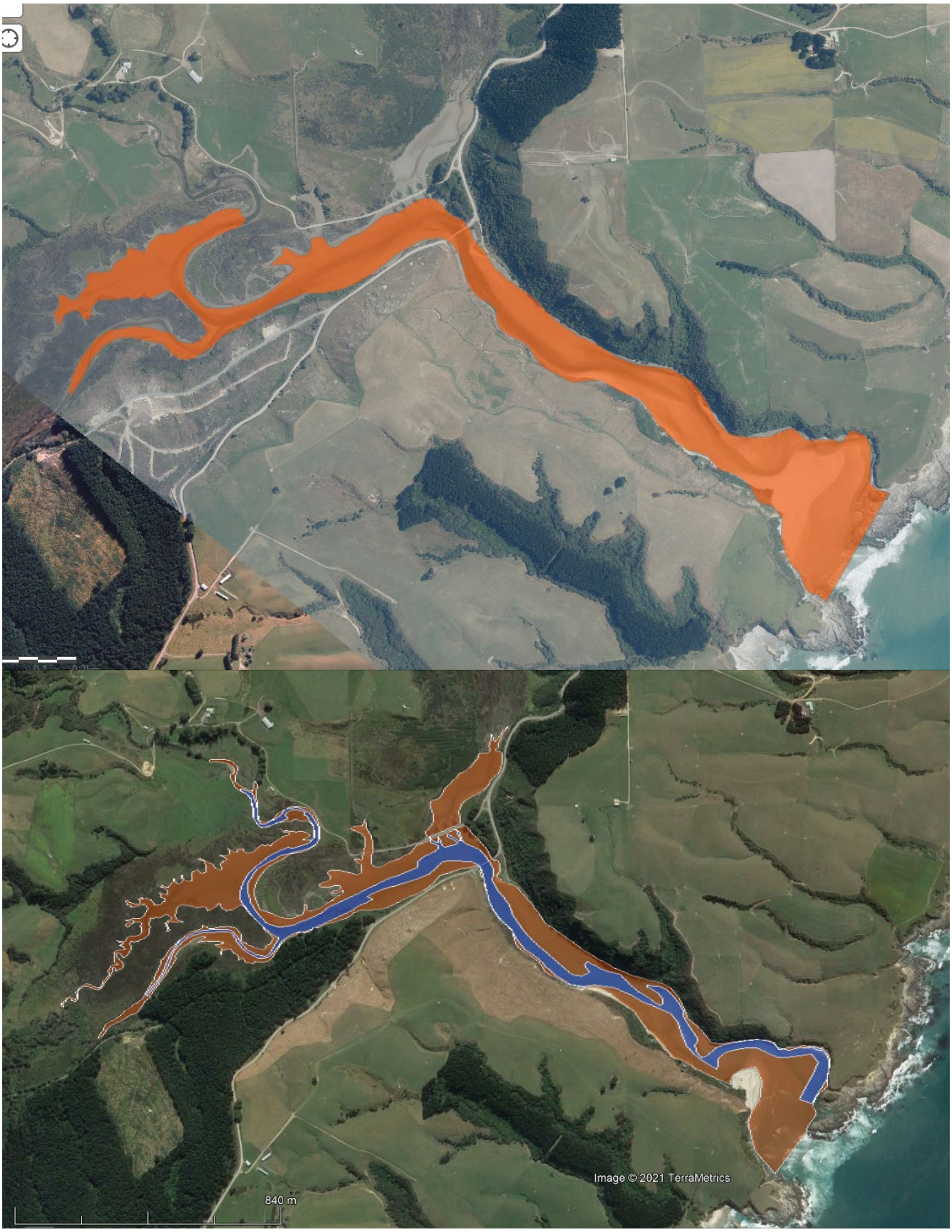

Figure A-14: Akatore Estuary extends from (upper) Coastal Explorer and (lower) re-measured from satellite images. The high and low tide surface areas of Akatore Estuary were remeasured using satellite images from Google Earth for 16 March 2016 and 1 September 2019.

Figure A-15: Tokomairoro Estuary extents from (left) Coastal Explorer and (right) surveyed in 2019. The 2019 NIWA survey detected saline intrusion extending approximately 10 km upstream of the estuary mouth.

Figure A-16: Clutha River. The shapefile from Coastal Explorer shows the Clutha River estuary extending as far inland as Balclutha. The Clutha River has a high flow and the lower reaches are likely freshwater dominated. The actual extent of the estuarine portion of the river is not known, so the Clutha River is excluded from this analysis.

Figure A-17: Pounawea (Catlins) Estuary. The estuary was surveyed by NIWA in 2018. The estuary extents from the 2018 survey are consistent with those from Coastal Explorer.

Figure A-18: Tahakopa Estuary. Tahakopa Estuary is classified as a Tidal lagoon (permanently open). Estuary extents shown are from Coastal Explorer.

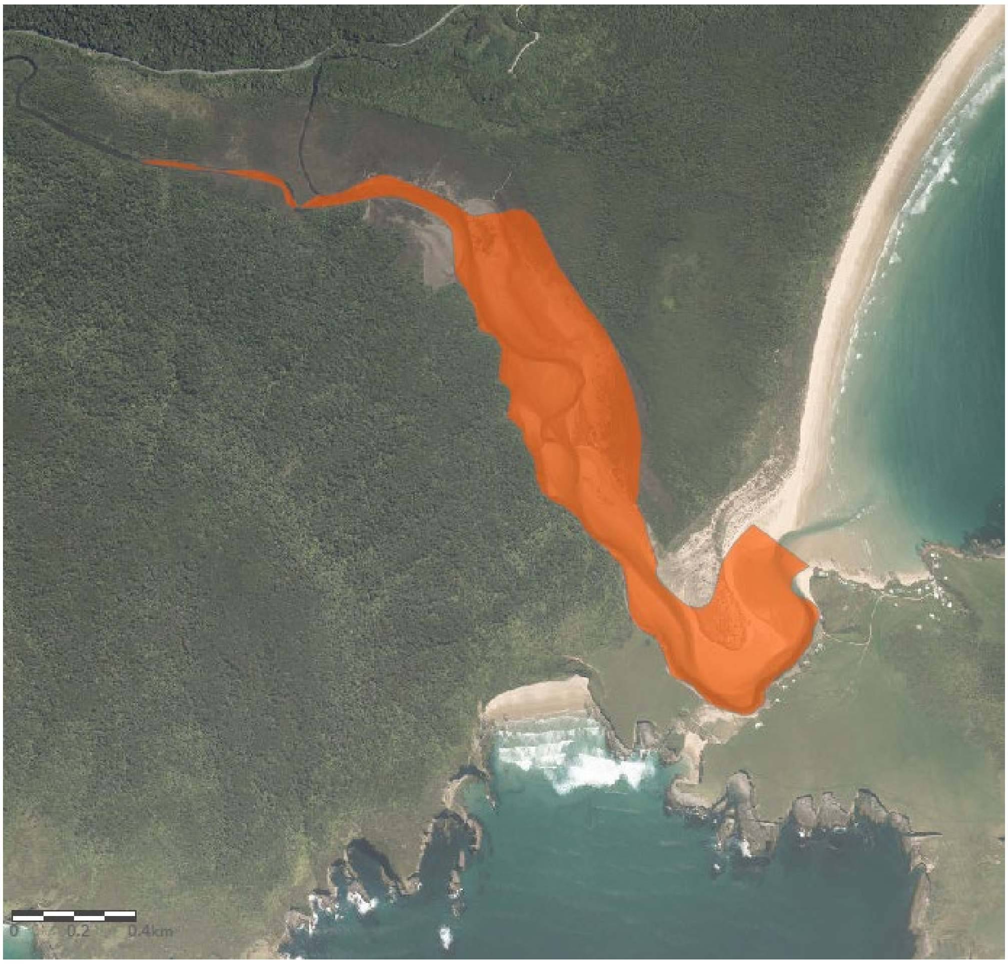

Figure A-19: Tautuku Estuary. Tautuku Estuary is a Tidal lagoon (permanently open). Estuary extents shown are taken from Coastal Explorer.

Figure A-20: Waipati (Chaslands) Estuary. Waipati (Chaslands) Estuary is a Tidal lagoon (permanently open). Because the percentage of the estuary area that is intertidal in Coastal Explorer (shapefile plotted at left) appeared too low, the estuary surface area was remeasured using satellite image from 19/3/2019 (hightide) and 21/4/2019 (low tide).