Eutrophication susceptibility assessment of Tokomairiro Estuary

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Executive summary

Otago Regional Council (ORC) wishes to assess the susceptibility of the Tokomairiro Estuary to nutrient loading. This information will provide insight to the trophic conditions likely to result from nutrient loads specified in the Regional Water Plan. ORC commissioned NIWA to calculate the eutrophication susceptibility of this estuary according to the recently released Envirolink screening tool 1 for the New Zealand Estuary Trophic Index (ETI). NIWA was also asked to calculate nutrient loads to this estuary that correspond to each of the four ETI trophic condition bands. River water quality and flow data for this work were provided by ORC.

Bathymetric surveys were conducted for the Tokomairiro Estuary during May 2019 to obtain accurate estuary surface areas and volumes for eutrophication susceptibility calculations.

We calculated eutrophication susceptibility of this estuary using two comparable ETI methods: the Assessment of Estuarine Trophic Status or 'ASSETS' approach, and the 'dilution modelling' approach (also called the CLUES-Estuary approach). The latter approach is considered more appropriate for small estuaries like the Tokomairiro Estuary where there is low dilution of in-flowing river water by sea water.

Under current flow conditions, the ASSETS approach used in ETI tool 1 put the Tokomairiro Estuary within the **moderate physical susceptibility** banding. The Tokomairiro Estuary has a **high N-load susceptibility** under the ASSETS approach, based on the N-load, flow data and bathymetric data collected for this study. The combination of a 'Moderate' physical susceptibility, and a 'High' N load susceptibility results in a **high combined physical and nutrient load susceptibility (Band C)**, according to the ASSETS approach.

Using the dilution modelling estimate of eutrophication susceptibility, the Tokomairiro Estuary has an ETI susceptibility score in **Band D (Very High) for susceptibility to eutrophication**.

The overall estuary ETI score of the Tokomairiro Estuary derived from recent field measurements (Band C) is lower than that calculated in this report based on its nutrient loading and physical characteristics (Band D). Of note, the observed macroalgal biomass in the estuary is lower than expected based on the modelled susceptibility metrics in this report. This is particularly pertinent to the lower estuary, where most of the available intertidal habitat for macroalgal growth is located. In contrast, field-measured phytoplankton in deeper areas of the mid and upper areas of the estuary, and sediment conditions in the mid and upper estuary broadly match those predicted for estuaries like Tokomairiro with ETI susceptibility within Band D. The differences between observed estuarine state and that predicted using dilution modelling can be addressed by using a two-compartment dilution model, separating upper and lower sections of the estuary. In this two-compartment model, the upper estuary has an ETI susceptibility score in **Band D (Very High) for susceptibility to eutrophication**, while the lower estuary has an ETI susceptibility score in **Band B (moderate) for susceptibility to eutrophication**.

To aid management decisions, we present the catchment loadings for total nitrogen (TN) and dissolved inorganic nitrogen (DIN) required to lie within the A, B, C or D bands for eutrophication susceptibility in Tokomairiro Estuary. Because the upper estuary shows the highest susceptibility to both macroalgal and phytoplankton blooms, the nutrient load bands are based on the predicted response of the upper estuary using the two-compartment model.

1 Introduction

To gain an understanding of how future changes to freshwater volumes and nutrient flows may affect the ecological health of the Tokomairiro Estuary, Otago Regional Council (ORC) requested that NIWA determines the eutrophication susceptibility of this estuary using Envirolink screening tool 1 for the New Zealand Estuary Trophic Index (Robertson, Stevens et al. 2016a; Zeldis, Plew et al. 2017).

This work included the following:

- Determination of estuary type according to ETI tool 1;
- Application of ETI tool 1 methods for current flow and nitrogen (N) loading conditions;
- A bathymetric survey of the estuary to measure estuary volume and area;
- Determination of the flushing and dilution potential of the estuary according to the Assessment of Estuarine Trophic Status (ASSETS) approach of ETI tool 1 using freshwater inflow data provided by ORC, as well as estuary volume and tidal height data;
- Calculation of the physical susceptibility of the estuary according to the ASSETS approach;
- Calculation of estuary areal N loads for the estuary;
- From the estuary volume and area, and nutrient and freshwater loads from the previous steps, calculation of the combined physical and nutrient load susceptibility of the estuary, according to the ASSETS approach;
- A dilution modelling approach (Plew, Zeldis et al. 2018) to estimate potential nutrient concentrations, as an alternative way to assess eutrophication susceptibility. This was used because the ASSETS approach under-estimates susceptibility, particularly for small estuaries with volumes <2.8 million m^3 (Robertson, Stevens et al. 2016a, page 30);
- Brief narrative guidance on the ecological condition that corresponded to the modelled susceptibility scores for the estuary, and comparison of this information with recent ecological monitoring data;
- Calculation of riverine N loads that correspond to A, B, C or D bands for eutrophication susceptibility in the estuary based on the dilution modelling approach.

Freshwater flows to the Tokomairiro Estuary are dominated by the Tokomairiro River. Freshwater flows from rivers from rivers and the nutrient loads they carry are heavily dependent on land use within catchments (Larned, Snelder et al. 2016). The ocean also provides a source of nutrients.

Nitrogen (N) availability most commonly limits peak seasonal algal growth in estuaries (Howarth and Marino 2006). Hence, N supplies from inflows and nutrient retention within estuaries are used to gauge estuarine eutrophication susceptibility. Freshwater inflow volumes influence the susceptibility of estuaries to eutrophication because flow rates affect the residence time of water within the estuary. Longer residence times have the potential to produce more eutrophic conditions because algae in the water column (phytoplankton) have time to grow and multiply within the estuary, and freshwater-derived nutrient loads that supply both phytoplankton and macroalgae are less quickly exported from estuaries and diluted by mixing with ocean water.

Here, we assess the susceptibility of the Tokomairiro Estuary to eutrophication based on the N-loading and flow information provided to NIWA, and the bathymetric characteristics of the estuary.

2 Flow and N-load calculations

Estuary N loads were calculated using a combination of observed and modelled nutrient loads and flows. ORC provided 22 years of flow and nutrient data for the Tokomairiro River at West Branch Bridge. This site is some 20 km upstream of the estuary, and there are other tributaries of the Tokomairiro River that join downstream of this monitoring site. To estimate loads and flows from the unmonitored and ungauged parts of the catchment, we make use of statistically predicted nutrient concentrations and flows (Booker and Woods 2014) which are freely available via the NIWA web-tool NZRiverMaps (https://shiny.niwa.co.nz/nzrivermaps/). The following steps are followed.

1. Mean flows and nutrient concentrations are calculated from observations at West Branch Bridge.
2. Predicted flow parameters and nutrient concentrations from NZRiverMaps for the West Branch Bridge site and the upstream extent of the Tokomairiro Estuary.
3. Ratios are calculated between each of the predicted values at the inlet of the Tokomairiro Estuary and West Branch Bridge sites.
4. The ratios calculated above are used to scale up the observed flows and concentrations at West Branch Bridge to obtain estimates of inputs to the Tokomairiro Estuary.

Observed total nitrogen (TN) loads in the Tokomairiro River at West Branch Bridge were variable from year to year (Figure 2-1) but show a statistically significant ($P = 0.002$) increase of 0.96 T/y (95% confidence interval 0.39-1.53 T/y). Annual mean flows have not increased significantly ($P = 0.48$, Figure 2-2) but concentrations have ($P < 0.001$, Figure 2-3). Increases in load are therefore attributable to increased total nitrogen concentrations.

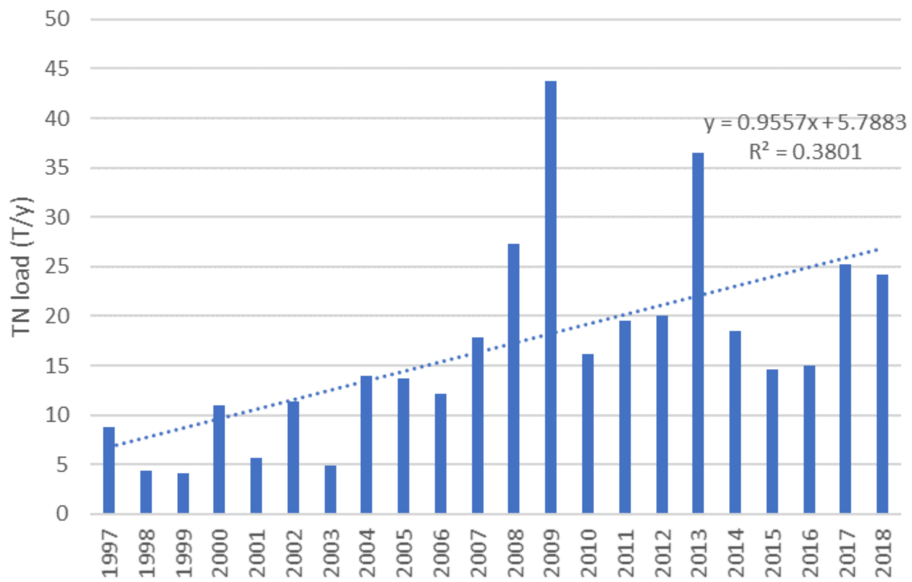

Figure 2-1: Annual mean total nitrogen loads in the Tokomairiro River at West Branch Bridge. Annual loads calculated from daily mean flows @ West Branch Bridge and TN concentrations interpolated from nutrient samples @ West Branch Bridge.

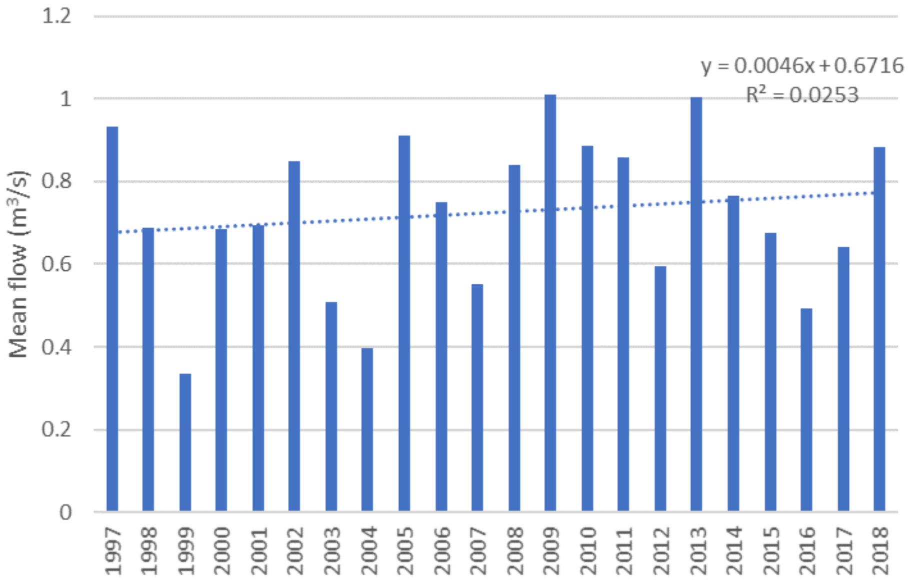

Figure 2-2: Annual mean flows measured at West Branch Bridge.

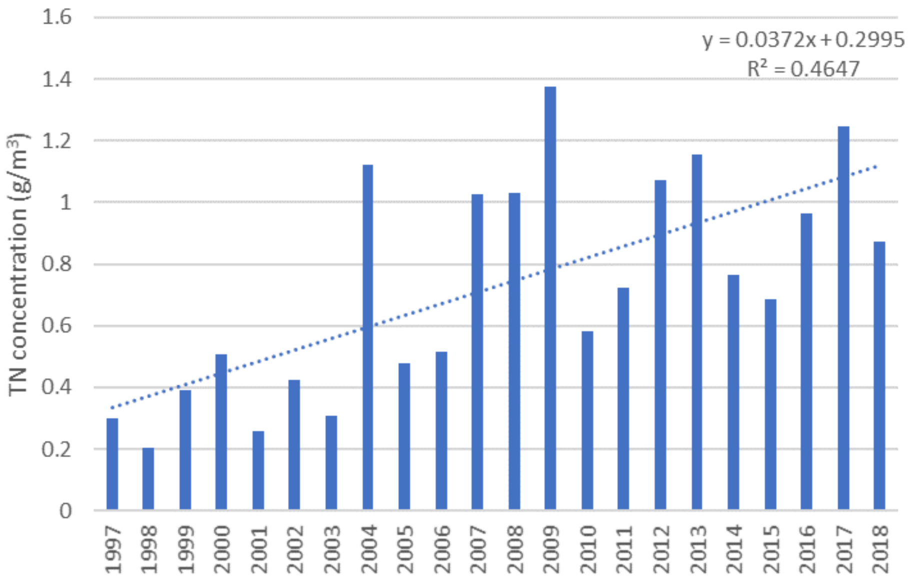

Figure 2-3: Annual mean total nitrogen concentrations in the Tokomairiro River as measured at West Branch Bridge.

We used the average load over the past five years in our calculations to provide a degree of smoothing of inter-annual variability while being representative of recent catchment loadings (Table 2-1). Five years is also the period of time used for State of Environment reporting (e.g., Larned, Snelder et al. 2016; Dudley, Zeldis et al. 2017). Current loads in the Tokomairiro River at West Branch Bridge (5-year average from 2014 to 2018) are 19,500 kg/y total nitrogen (TN) and 807 kg/y total phosphorus (TP). Dissolved inorganic nitrogen (DIN = nitrate + nitrite + ammonia) accounts for 62% of total nitrogen and dissolved reactive phosphorus (DRP) accounts for 27% of total phosphorus.

Table 2-1: Mean flows and mean annual loads measured in the Tokomairiro River at West Branch Bridge. Mean annual loads are averaged over 2014-18. The West Branch Bridge is approximately 20 km inland of the Tokomairiro Estuary, so the figures in this table represent only part of the inputs to the Tokomairiro Estuary.

Mean flow (m^3/s)	TN load (kg/y)	DIN load (kg/y)	TP load (kg/y)	DRP load (kg/y)
0.692	19,510	12,100	807	221

Loadings also show a seasonal pattern (Figure 2-4) with highest TN and DIN loads occurring over winter months (May-August). The comparatively high TN and DIN loads in November are due to a large flood on 20-Nov-2018.

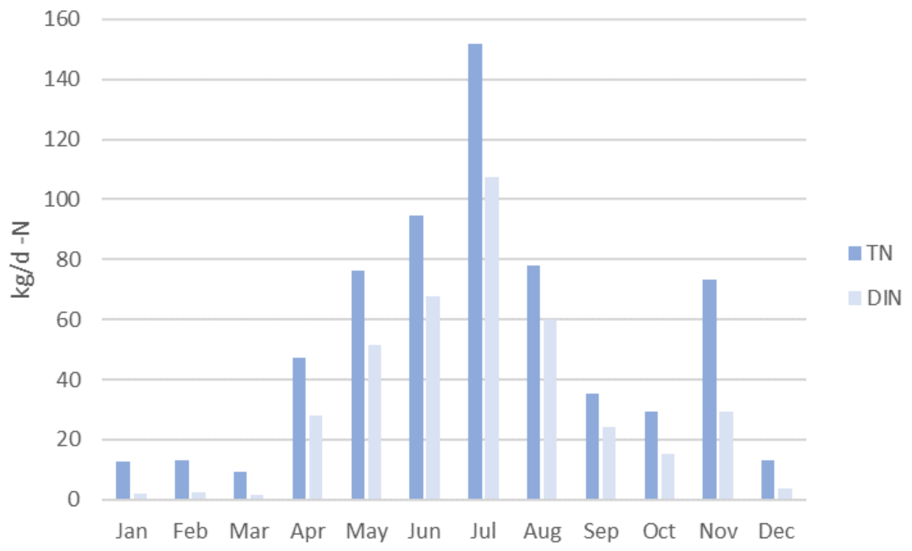

Figure 2-4: Seasonality of nitrogen loads from the Tokomairiro River 2014-2018. Based on data provided by Otago Regional Council from Tokomairiro River at West Branch Bridge.

Statistically predicted mean flows and median nutrient concentrations for the West Branch Bridge site and the headwaters of the estuary (from NZRiverMaps) are compared in Table 2-2. Observed values at West Branch Bridge are also provided as a comparison with the modelled values. The modelled nitrogen concentrations (DIN and TN) are in good agreement (within 2% and 8% respectively) with observed values, phosphorus is overestimated by 72% for DRP and 20% for TP, and modelled mean flow is 72% higher than observed.

Table 2-2: Observed and modelled mean flow and median nutrient concentrations at the Tokomairiro West Branch Bridge site and at the estuary headwater. Modelled values are obtained from NZRiverMaps. The ratio of the flows and nutrient concentrations between the two sites are used to adjust observed values at West Branch Bridge to account for ungauged parts of the catchment below the West Branch Bridge site.

	Observed @ West Branch Bridge	NZRiverMaps @ West branch bridge	NZRiverMaps @ Estuary	Ratio modelled Estuary/Bridge
Mean flow (m^3/s)	0.692	1.190	3.85	3.235
Median DIN (mg/m^3)	288	283	388	1.37
Median TN (mg/m^3)	575	527	649	1.23
DRP (mg/m^3)	10	17.2	20.4	1.19
TP (mg/m^3)	32.5	46.8	56.3	1.20

The ratios in the final column of Table 2-2 are used to adjust the observed flows and loads at West Branch Bridge (Table 2-1) to estimate the nutrient loads to estuary. Flows are adjusted by multiplying by the flow ratio (3.231). Loads are adjusted by assuming that mean and median nutrient concentrations scale similarly, and load is scaled by multiplying by the flow ratio and the appropriate nutrient concentration. Based on these ratios, we estimate that the Tokomairiro Estuary receives nutrient loads of 77,700 kg/y TN and 3,140 kg/y TP (Table 2-3).

Table 2-3: Mean flow and nutrient loads to the Tokomairiro Estuary. Flows and nutrient loads have been calculated by observations from the Tokomairiro River at West Branch Bridge from 2014-18, using statistically modelled flows and loads from NZRiverMaps to account for ungauged parts of the catchment.

Mean flow (m^3/s)	TN load (kg/y)	DIN load (kg/y)	TP load (kg/y)	DRP load (kg/y)
2.239	77,700	53,700	3,140	850

3 Bathymetric surveys

Bathymetric surveys were conducted for the Tokomairiro Estuary to obtain accurate estuary surface areas and volumes. The Tokomairiro Estuary was surveyed 30 April – 2 May 2019 using a combination of a boat-mounted Sonarmite echosounder to measure depths, and drone-based LIDAR to measure topography of intertidal areas (Figure 3-1). Elevations were referenced to New Zealand Vertical Datum 2016 (NZVD2016). Bathymetry was mapped as far as 10 km upstream of the estuary mouth. The estuary bathymetry is displayed in Figure 3-2.

Figure 3-1: Bathymetric surveying. Bathymetry of submerged areas were mapped using a boat-mounted Sonarmite echosounder, with positions recorded with RTK-GPS. Intertidal areas were mapped with a drone-mounted LiDAR USA laser scanner.

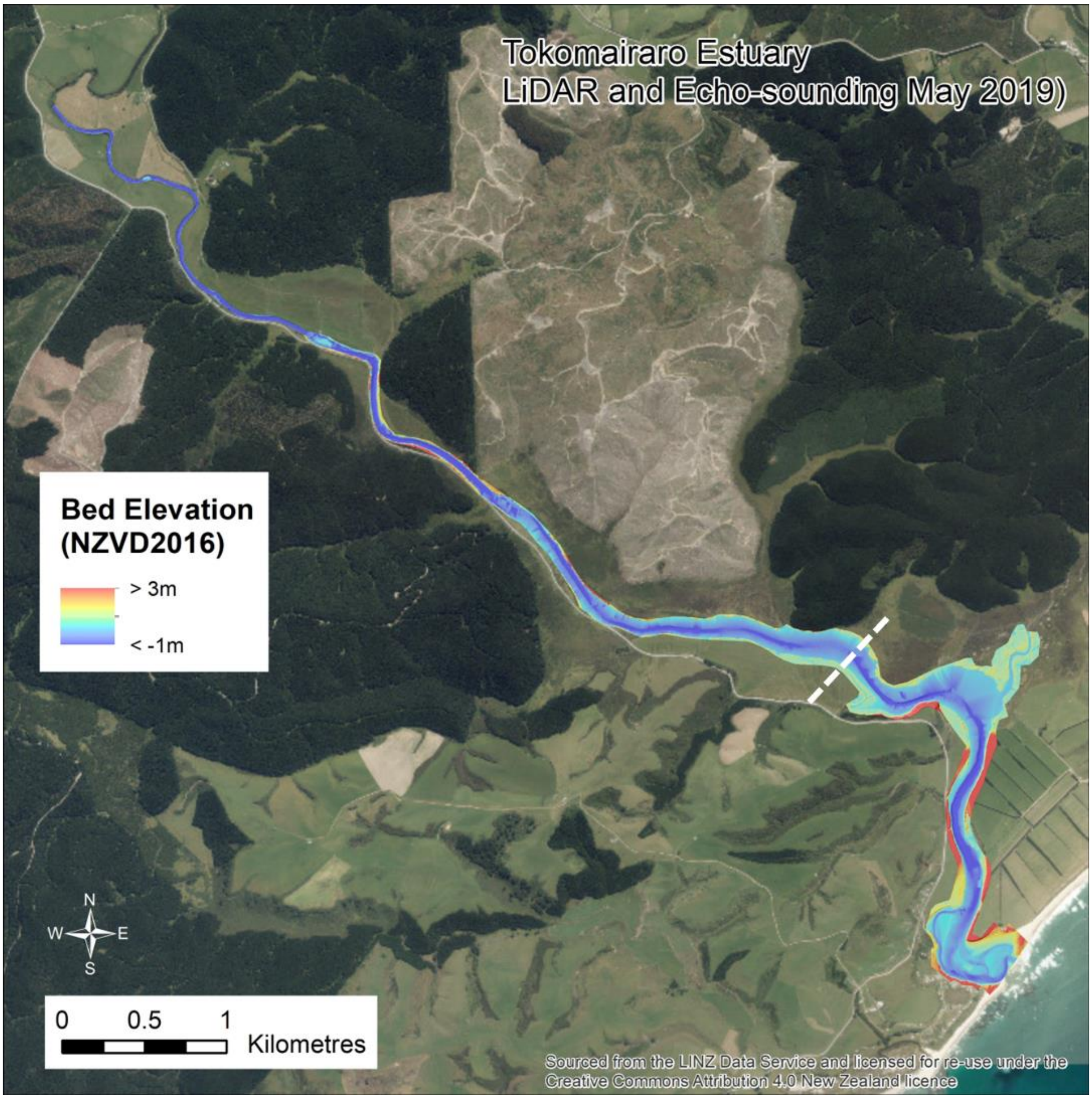

Figure 3-2: Surveyed bathymetry of the Tokomairiro Estuary. Bathymetry data compiled from echosounder and drone-based laser scan surveys conducted 30 April – 2 May 2019. Elevations are relative to NZVD 2016. The white dashed line shows where we have separated the upper and lower estuary when using the two-compartment dilution model in our analysis.

Salinities were measured along the length of the estuary at high tide (13:10 – 15:34 2 May 2019) both to determine the upstream extent of the estuary, and for tuning the dilution model. At the time of our survey, we determined that the Tokomairiro Estuary was influenced by salinity up to 9.8 km inland from the coast (Figure 3-3). However, we note that one of the fine scale monitoring sites of Robertson and Robertson (2018) was a further 1.3 km upstream, and they measured surface and bottom salinities of 10 and 27 ppt respectively. The flow over the 7 days prior to their measurements averaged 0.150 m^3/s, whereas our measurements were taken after a 7-day average flow of 290 m^3/s which may have moved the saline influence downstream.

Consequently, there is some ambiguity as to the upstream extent of the estuary. Our mapped bathymetry stops about where we observed the salt wedge reaching (9.8 km). Upstream from here, the river channel is steep-sided. To approximate the unmapped upper extents of the estuary, we have assumed that this region has an average bed elevation of -1.0 m, width 20 m, and length 1.5 km. This adds approximately 5% to the total area and volume of the estuary.

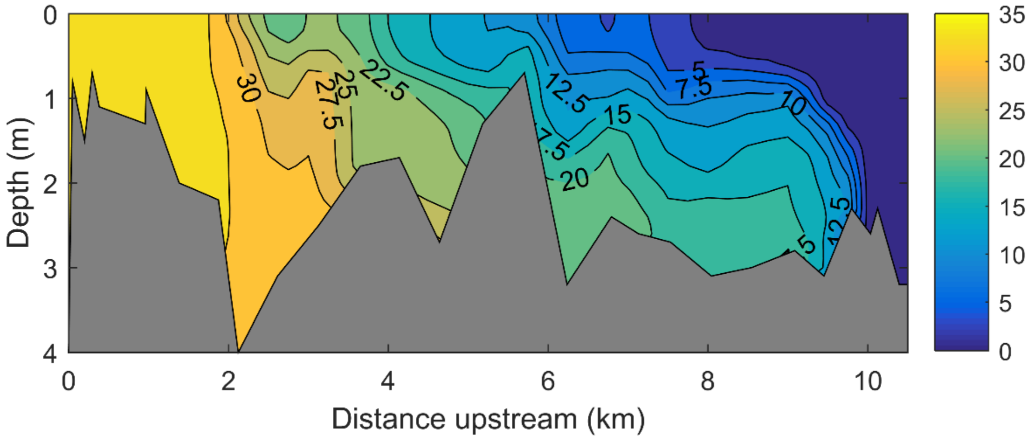

Figure 3-3: Profiles of salinity recorded along the length of the Tokomairiro Estuary on 2 May 2019. The presence of saline water was detected up to 9.8 km upstream of the estuary mouth.

Water level data (Figure 3-4) obtained by ORC over the period 21 January 2019 to 18 June 2019 were used to obtain high tide volumes, tidal prisms, and intertidal area. Water levels in the estuary fluctuated with tide, but also showed long term changes in mean water level. Some of the increases in water level occurred when flow increased, but other changes in mean water level are likely attributable to changes in the estuary mouth. Tidal range generally increased with water level, suggesting that wider mouth openings result in higher mean water levels and larger exchange with the ocean. However, there is a period from 5-12 June where mean water levels steadily increased while tidal range decrease to 0 m by the 8th of June, indicating the mouth was either closed or elevated sufficiently that the estuary was not affected by tides.

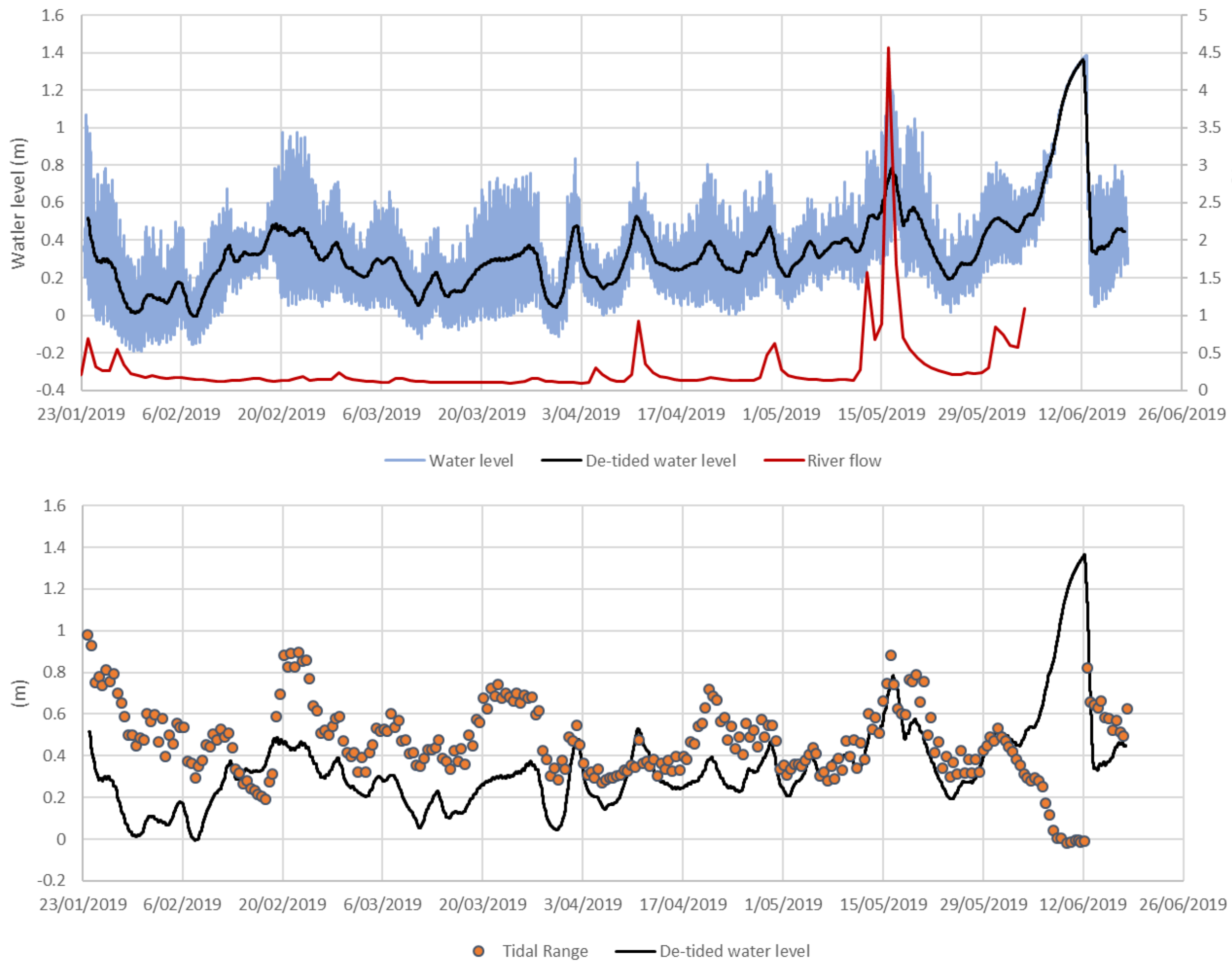

Figure 3-4: (Upper plot) observed water levels, de-tided water levels in the Tokomairiro Estuary and flows in the Tokomairiro River at West Branch Bridge. (Lower plot) tidal range and de-tided water level in the Tokomairiro Estuary.

Because of the long-term variations in tidal range and mean water level, we defined spring high tide as the 95th percentile of water levels recorded at high tide (0.972 m), and spring tide tidal range as the 95th percentile of tidal ranges (0.792 m). We ignore data between 5-12 June when the mouth of the estuary was closed or closing.

Spring tide tidal prism was calculated as the difference in estuary volume between spring high tide and spring high tide less the spring tidal range (0.972 – 0.792 = 0.180 m). Note that tidal prism calculated in this manner was within 1% of the 95th percentile of observed tidal prisms. Surface areas, tidal range, volumes and surface areas are reported in Table 3-1.

Table 3-1: Physical properties of the Tokomairiro Estuary.

Surface area at spring high tide (m^2)	Intertidal area	Tidal range (spring) (m)	Volume at spring high tide (m^3)	Spring tidal prism (m^3)	Mean depth (MHWS) (m)
1,077,000	23%	0.792	1,459,000	760,000	1.36

4 Estuary typology

The physical characteristics of an estuary, such as depth and intertidal area, strongly influence its susceptibility to eutrophication caused by nutrient loads from land. We classified the Tokomairiro Estuary by physiographical type according to ETI tool 1.

Based on these data, the estuary is classified as a Shallow, Short Residence-time Tidal River Estuary (SSRTRE), defined in ETI tool 1 as <3 m depth with intertidal area comprising <40 per cent of total estuary area. Eutrophication susceptibility calculations appropriate to this estuary type are applied in the following sections.

The estuary shows feature typical of SSRTREs. The lower basin is generally well flushed with sea water, although the mouth is dynamic and can constrict or close to the sea. A high tide, the lower basin is approximately 500 m long by 250 m wide (Figure 4-1). The estuary bed in the lower basin is mostly sandy, and water clarity was high at the time of the survey.

Figure 4-1: Lower reaches and mouth of the Tokomairiro Estuary. Photograph taken by drone from ~300 m upstream of the mouth, looking towards the ocean, 1 May 2019.

Upstream, the estuary narrows to 70-80 m in width. Water becomes increasingly brackish, and sediments become muddier (Figure 4-2).

Figure 4-2: Lower reaches of the Tokomairiro Estuary, looking upstream. The photograph was taken from ~300 upstream of the estuary mouth, and shows the estuary with width of 70-80 m, extending ~ 1 km to a sharp bend to the left.

There are large marshlands/wetland areas alongside the mid-reaches of the estuary, although these are not normally submerged, with the estuary confined between clear banks (Figure 4-3). Further upstream the estuary becomes increasingly riverine in appearance. Water clarity was noticeable lower in the mid and upper estuary compared to in the lower estuary.

Figure 4-3: Mid-reaches of the Tokomairiro Estuary looking upstream. This photograph was taken from a hillside ~ 1.5 km inland from the sea. A large marshland area can be seen on the right (true left). The estuary continues upstream for a further ~10 km.

5 ASSETS susceptibility assessment

5.1 Flushing potential

Flushing potential was calculated according to the ASSETS approach described in ETI tool 1. This approach defines an estuary's flushing potential as:

[daily freshwater inflow (m^3/d)]/ estuary volume (m^3).

Estuaries can then be classified using the resulting value as having a high, moderate or low flushing potential.

The Tokomairiro Estuary has a moderate tidal range (0.792 m). The mean daily inflow is 1.93×10^5 m^3/day and the estuary volume is 1,459,000 m^3. The flushing potential for the estuary is 0.13. Comparison with the ETI bandings of flushing potentials for mesotidal estuaries (high: $10^0 – 10^{-1}$; moderate: 10^{-2}, and low: $10^{-3} – 10^{-4}$) shows that the Tokomairiro Estuary flushing potential is high.

Table 5-1: Calculated flushing potentials for the Tokomairiro estuary. Based on Estuarine Trophic Index tool 1 (Robertson, Stevens et al. 2016a).

Mean annual freshwater input (m^3/day)	Estuary volume at spring high tide (m^3)	Flushing potential	Flushing potential band (ETI tool 1)
1.93×10^5	1,459,000	0.13	High

5.2 Dilution potential

The ASSETS approach defines dilution potential as:

1/estuary volume (cubic feet).

Counter-intuitively, using this method the larger the estuary (and greater the dilution of inflowing fresh waters), the smaller the dilution potential value.

Dilution potential for Tokomairiro Estuary is 1.9×10^{-8}, which is outside of the range of bands defined in ASSETS (we assumed no or minimal water column stratification). The ASSETS classification is based on substantially larger estuaries and appears untested for estuaries as small as Tokomairiro Estuary. Thus, in the absence of defined dilution potential bandings for small estuaries, we define this estuary as having a low dilution potential.

5.3 Physical susceptibility

Under current flow conditions, the high flushing potential and low dilution potential scores identify the Tokomairiro Estuary as moderately physically susceptible, using the ASSETS categories (Table 5-2).

Table 5-2: ASSETS physical susceptibility classification system for shallow intertidal-dominated estuaries. Table from ETI tool 1 (Robertson, Stevens et al. 2016a).

		Dilution potential		
		High	Moderate	Low
Flushing potential	High	Low physical susceptibility	Low physical susceptibility	Moderate physical susceptibility
	Moderate	Low physical susceptibility	Moderate physical susceptibility	High physical susceptibility
	Low	Moderate physical susceptibility	High physical susceptibility	High physical susceptibility

We note that the ASSETS approach appears to under-estimate the physical susceptibility of the Tokomairiro Estuary because its dilution potential is substantially less than those for estuaries used to develop the ASSETS approach. Hence, we recommend considering the dilution model-derived calculation of eutrophication susceptibility for this estuary (see section 6 below).

5.4 Nutrient load susceptibility

ASSETS nutrient load susceptibilities are categorised from areal nitrogen loads (Table 5-3).

Tokomairiro Estuary had a loading of 198 mg/m^2/d, which indicates a high N-load susceptibility.

Table 5-3: Areal N-load susceptibility for Tokomairiro Estuary under current N loads. Based on Robertson, Stevens et al. (2016a) Estuarine Trophic Index tool 1.

Estuary	Sum of mean annual N-loads - all tributaries (kg/year)	Estuary surface area at high water spring (km^2)	Areal N load (mg/m^2/day)	N load susceptibility band (ETI tool 1)
Tokomairiro Estuary	77,700	1.460	198	High (50–250 mg/m^2/day)

5.5 Combined physical and nutrient load susceptibility

Under the present flow and nutrient loading conditions, we assessed the Tokomairiro Estuary having a moderate physical susceptibility and a high N load susceptibility, based on its estuary volume area, nutrient loads and freshwater flows. According to the ASSETS approach in ETI tool 1, this combination results in a **high combined physical and nutrient load susceptibility** (Band C) (Table 5-4).

Table 5-4: Combined physical and nutrient load susceptibility bandings for shallow intertidal-dominated estuaries. Table from ETI tool 1 (Robertson, Stevens et al. 2016a).

		N load susceptibility (mg/m^2/day)			
Physical susceptibility		Very high (>250)	High (50–250)	Moderate (10–50)	Low (<10)
	High	Band D Very High	Band C High	Band C High	Band B Moderate
	Moderate	Band D Very High	Band C High	Band B Moderate	Band A Low
	Low	Band C High	Band B Moderate	Band B Moderate	Band A Low

6 Estuary Trophic Index susceptibility

6.1 Background to the ETI dilution modelling for susceptibility approach

Because the ASSETS approach employed in the ETI tool under-estimates susceptibility, particularly for small estuaries with volumes <2.8 million m^3 (Robertson, Stevens et al. 2016a, page 30), we used a dilution modelling approach (Plew, Zeldis et al. 2018) to estimate potential nutrient concentrations, as an alternative way to assess eutrophication susceptibility. The dilution modelling approach scores susceptibility to excessive phytoplankton growth and to excessive macroalgal growth separately, as two predictors of ecological impact, as described in the ETI tool 1 (Zeldis, Plew et al. 2017) (Table 6-1).

The dilution modelling approach predicts the average potential nutrient concentrations in the estuary. Potential nutrient concentrations are those that would occur in the absence of nutrient sources or sinks in the estuary, such as uptake into algae or losses through denitrification. Potential concentrations are expected to be higher than observed concentrations, because observed concentrations show the remaining nutrients in the water column after some have been removed or taken up. Potential nutrient concentrations are a stronger indicator of eutrophication susceptibility than observed values because much of the N taken up into algae results in algal growth (Plew, Zeldis et al. 2018).

The ETI gives bandings for susceptibility to eutrophication due to opportunistic macroalgal blooms based on total nitrogen. The bandings for TN are:

- A: < 80 mg/m^3,
- B: 80 mg/m^3 – 200 mg/m^3,
- C: 200 mg/m^3 – 320 mg/m^3,
- D: >320 mg/m^3.

The expected condition of the estuary for each band is described in Table 6-1. The thresholds between each band are based on a comparison of potential concentrations with observations of opportunistic macroalgae from over 20 New Zealand estuaries (Plew, Zeldis et al. 2019). Observations of macroalgal impact were taken in summertime, while the potential nitrogen concentrations were calculated from annual nitrogen loads and mean flow. The thresholds between bandings should not be regarded as absolute, rather they are indicative of shifts along a continuum of eutrophic state. The changes between ecological conditions described in Table 6-1 occur gradually with increasing concentration rather than abruptly. The thresholds between the concentration bands are indicative of where transitions between these ecological conditions are expected. We caution that other factors may influence the macroalgal response in an estuary besides nutrient load, for example the availability of suitable substrate for macroalgal growth and bioavailability of nutrients (e.g., the dissolved vs particulate ratios in the TN and ammonia to nitrate ratios). Macroalgae are seldom limited by phosphorus (Atkinson and Smith 1983; Plew, Zeldis et al. 2019), thus it is appropriate to develop bandings based on nitrogen only.

Susceptibility to phytoplankton blooms are determined from potential TN and TP concentrations and flushing time using a growth model (Figure 6-1). While previous reports to ORC have used a growth model based only on nitrogen, a revised model has been created that includes phosphorus (Plew, Zeldis et al. 2019). While the majority (80%) of New Zealand's estuaries that are susceptible to phytoplankton are nitrogen limited (Plew, Zeldis et al. 2019), phosphorus can be the growth limiting nutrient at N:P molar ratios of > ~20:1. The growth model is used to estimate the potential chlorophyll-*a* concentration, which represents the maximum likely chlorophyll-*a* concentration that is likely to occur based on the available nutrients and flushing time. This concentration is related to a susceptibility band as reported in Table 6-1. The growth model shows that estuaries with short flushing times (<3.3 days) are highly unlikely to have phytoplankton blooms as they are flushed from the system faster than they can grow.

Table 6-1: Description of ecological quality for macroalgal and phytoplankton bandings. Adapted from ETI tool 2 (Robertson, Stevens et al. 2016b) and Plew, Zeldis et al. (2019). The bandings for predicted Chl-*a* are for meso/polyhaline estuaries, defined as estuaries with salinities between 5-30 ppt.

Band	**A** **Minimal eutrophication**	**B** **Moderate eutrophication**	**C** **High eutrophication**	**D** **Very high eutrophication**
Opportunistic Macroalgae	$TN_{est} < 80$ mg/m^3 Ecological communities (e.g., bird, fish, seagrass, and macroinvertebrates) are healthy and resilient. Algal cover <5% and low biomass (<100 g/m^2 wet weight) of opportunistic macroalgal blooms and with no growth of algae in the underlying sediment. Sediment quality high	$80 \leq TN_{est} < 200$ mg/m^3 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 (100–200 g/m^2 wet weight) of opportunistic macroalgal blooms and with no growth of algae in the underlying sediment. Sediment quality transitional	$200 \leq TN_{est} < 320$ mg/m^3 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 (>200– 500 g/m^2 wet weight), often with entrainment in sediment. Sediment quality degraded	$TN_{est} \geq 320$ mg/m^3 Ecological communities (e.g., bird, fish, seagrass, and macroinvertebrates) are strongly impacted by macroalgae. Persistent very high % macroalgal cover (>75%) and/or biomass (>500 g/m^2 wet weight), with entrainment in sediment. Sediment quality degraded with sulphidic conditions near the sediment surface
Phytoplankton	Chl-*a* < 5 µg/l Ecological communities are healthy and resilient	5 ≤ Chl-*a* < 10 µg/l Ecological communities are slightly impacted by additional phytoplankton growth arising from nutrients levels that are elevated	10 ≤ Chl-*a* < 16 µg/l Ecological communities are moderately impacted by phytoplankton biomass elevated well above natural conditions. Reduced water clarity likely to affect habitat available for native macrophytes	Chl-*a* ≥ 16 µg/l Excessive algal growth making ecological communities at high risk of undergoing a regime shift to a persistent, degraded state without macrophyte/seagrass cover

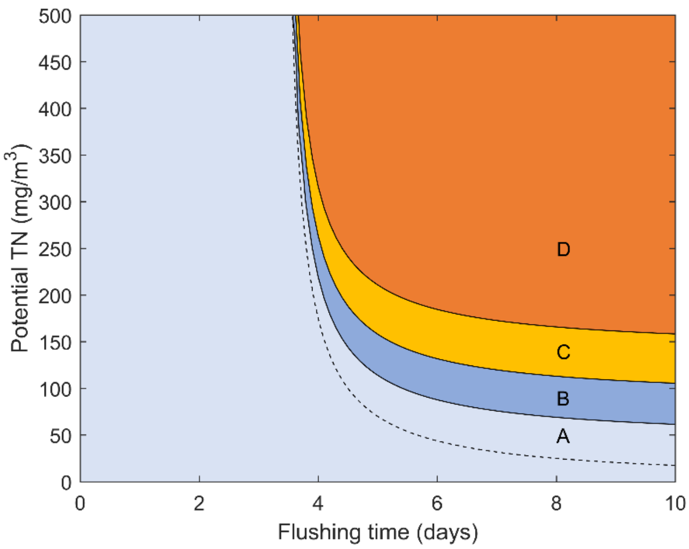

Figure 6-1: ETI susceptibility bandings for phytoplankton based on flushing time and potential total nitrogen concentrations. This graph shows model output based on an assumed half saturation coefficient of 35 mg/m^3 TN and a net specific growth rate of 0.3 day^{-1}. The solid curves indicate thresholds between ETI bandings, and below the dashed line phytoplankton are flushed from the estuary faster than they grow.

The dilution modelling approach uses simple models to account for the mixing between the inflowing river and sea waters, providing an estimate of the potential nutrient concentration (concentration present in the absence of denitrification or uptake) in the estuary averaged over time and space.

A modified tidal prism model (Luketina 1998) is used to calculate dilution for the Tokomairiro Estuary. The equations that describe the mixing model are given in Plew, Zeldis et al. (2018). This model includes a tuning parameter to account for return flow back into the estuary and incomplete mixing within the estuary. The tuning factor can be estimated from estuary-averaged salinity at high tide.

The tuning parameter is sensitive to the ratio of freshwater inflow to tidal prism (Plew, Zeldis et al. 2018). As freshwater inflow increases, the tuning factor decreases. This is illustrated in Figure 6-2 which shows tuning factors calculated for a range of estuaries. To account for changes in the tuning factor with flow, we assume that the relationship is similar to the regression shown in Figure 6-2, and described by

$$\boldsymbol{b} = \boldsymbol{b_0} \boldsymbol{e}^{-1.679\frac{\boldsymbol{QT}}{\boldsymbol{P}}} \qquad (1)$$

where b_0 is the reference tuning factor (the tuning factor at QT/P = 0, Q = freshwater inflow m^3/s, T the tidal period 12.42 x 3600 s, and P the tidal prism m^3), and is obtained by rearranging equation (1).

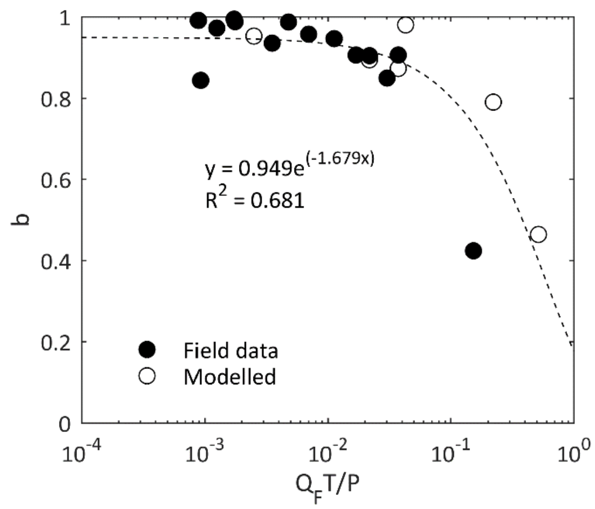

Figure 6-2: Variation of tuning factor with increasing ratio of freshwater inflow to tidal prism. The data shown are from a range of different estuaries. From Plew et al. (2018).

The model described here treats the estuary as a single compartment, which is useful for estimating estuary-wide response to nutrient loads. Because monitoring data show significant differences between the upper and lower parts of the Tokomairiro Estuary (Robertson and Robertson 2018; Stevens 2018), we also use a two compartment dilution model, originally developed for the Pounawea (Catlins) Estuary (Plew and Dudley 2018). Unlike the Pounawea Estuary, there is no clear or natural split between the upper and lower Tokomairiro Estuary. We chose to split the estuary approximately 2.7 km upstream of the estuary mouth. While somewhat arbitrary, splitting the estuary at this point means that all the large intertidal areas are contained in the lower estuary. The volumes and areas of the upper and lower estuary compartments are given in Table 6-2.

Table 6-2: Volumes and areas of the upper and lower Tokomairiro Estuary at spring tide. The location of the split between upper and lower estuary is shown in Figure 3-2.

	Volume (m^3)	Area (m^3)	Mean depth (m)	Intertidal area
Upper Estuary	799,000	495,000	1.61	14%
Lower Estuary	660,000	582,000	1.13	31%

6.2 Dilution modelling results – single compartment model

The dilution model for the Tokomairiro Estuary is tuned using salinities, freshwater inflows and tidal prisms observed during the field survey. When salinities were measured in the estuary, the tidal range was 0.361 m, and tidal prism 314,000 m^3. Mean flow recorded in the Tokomairiro River and West Branch Bridge was 0.196 m^3/s, but this excludes any tributaries further down the catchment. To include these, we scale up the observed flow at West Branch Bridge by a factor of 3.235 (Table 2-2) to obtain 0.438 m^3/s. The inputs to, and results of, this tuning procedure are given in Table 6-3. Note that the reference tuning factor b_0 has a value > 1. At very low flows, this will result in flow adjusted tuning factors >1 which are physically unrealistic. Although this was not necessary in our calculations below, we recommend setting flow adjusted b values to a maximum of 0.98.

Table 6-3: Calibration of the single compartment estuary mixing models.

Tidal prism (m^3)	Freshwater inflow (m^3/s)	Mean salinity	Observed tuning parameter b	Reference tuning factor b_0
314,000	0.438	20.15	0.951	1.056

Susceptibility assessments are conducted using mean annual loads and mean flows (see Table 2-3).

The dilution model indicates that under mean flow conditions, the Tokomairiro has a very high susceptibility to macroalgae (ETI Band D), but a low susceptibility to phytoplankton. While the model predicts some growth of phytoplankton (Chl-*a* of 3 µg/l), this is below the 5 µg/l threshold for Band B and thus meets the ETI Band A for phytoplankton susceptibility. However, stratification can occur in deep pockets within SSRTREs, and local flushing times of these areas may be sufficiently long that phytoplankton growth can be sustained. Consequently, there may be areas with high phytoplankton in deeper waters, or in other poorly flushed areas of the estuary.

Table 6-4: Results of single compartment dilution modelling for the Tokomairiro Estuary under mean flow and mean annual 2014–18 total nitrogen loads. The estuary is classified as a Shallow Short Residence-time Tidal River Estuary (SSRTRE), and as such the overall ETI susceptibility band is determined by the maximum of macroalgae and phytoplankton susceptibilities. Note that the estuary is treated as a single compartment, and inflows and loads are summed to estimate the inflow concentration.

Mean river TN (mg/m^3)	Mean river TP (mg/m^3)	Ocean TN (mg/m^3)	Ocean TP (mg/m^3)	Estuary freshwater fraction	Estuary TN (mg/m^3)	Estuary TP (mg/m^3)	Estuary flushing time (days)	Macroalgal susceptibility	Phytoplankton susceptibility	ETI susceptibility
777	31.4	40	1	48%	397	15.7	3.65	D	A	**D**

Under low flow conditions, or when the estuary mouth is constricted or closed, the flushing time of the estuary may increase sufficiently that wide-spread phytoplankton blooms can occur. To estimate the likely phytoplankton response of the estuary during low flow periods, we repeat the dilution modelling using mean February flow. We estimate this using a flow seasonality factor of 0.566 from NZRiverMaps (Booker and Woods 2014), which gives a mean February flow of 1.27 m^3/s. We also use mean summer (December to Febuary, 2014-2018) nutrient concentrations, estimated by scaling observations from the Tokomairiro at West Branch Bridge by the ratios in Table 2-2. Under this scenario, the predicted potential chlorophyll-*a* increases to 24 µg/l, which exceeds the threshold for an ETI Band D for phytoplankton susceptibility (Table 6-5). The molar ratio of N:P = 25:1 indicates that phytoplankton growth will likely be phosphorus limited under summer conditions.

Table 6-5: Calculation of phytoplankton susceptibility during summer conditions. February mean inflows have been estimated by scaling annual mean flows by a predicted flow seasonality factor. Riverine TN and TP concentrations are estimated by scaling observed Dec-Feb 2014-2018 mean concentrations from the Tokomairiro River at West Branch Bridge to account for ungauged sources.

Summer river TN (mg/m^3)	Summer river TP (mg/m^3)	Freshwater Inflow (m^3/s)	Estuary freshwater fraction	Salinity (ppt)	Estuary TN (mg/m^3)	Estuary TP (mg/m^3)	Estuary flushing time (days)	Predicted Chl-*a* (µg/l)	Phytoplankton susceptibility
549	50	1.27	58%	15	333	29	7.6	24	D

When the mouth closes, the flushing time will increase further, and nutrient concentrations will also increase as the fresh water content of the estuary increases. Both factors (increased flushing time and nutrient concentrations in the estuary) increase the potential for phytoplankton blooms to occur. Mouth closures are most common in summer low-flow periods, although the water level data indicate that closures could happen at any time of year (Figure 3-4).

6.3 Dilution modelling – two compartment model

The two compartment model, described in Plew and Dudley (2018), has separate tuning factors for the upper and lower estuary which are calibrated using salinity in a similar manner to the single compartment model. Results of the calibration are given in Table 6-6.

Table 6-6: Calibration of the two-compartment estuary mixing model.

	Tidal prism (m^3)	Freshwater inflow (m^3/s)	Mean salinity (ppt)	Observed tuning parameter b	Reference tuning factor b_0
Upper	148,300	0.438	13.9	0.885	0.987
Lower	154,900	0.438	31.1	0.311	0.347

Results of the two-compartment model for mean flow conditions are given in Table 6-7. Under mean flow conditions, the upper estuary has a very high (Band D) susceptibility to macroalgal blooms, while the lower estuary has moderate (Band B) macroalgal susceptibility. The flushing time under mean flow conditions is too short for phytoplankton growth to become widespread.

Table 6-7: Results of dilution modelling using the two-compartment model for the Tokomairiro Estuary under mean flow and mean annual 2014–18 total nitrogen loads. Calculations use mean river flow of 2.239 m^3/s, river inflow concentrations of 777 mg/m^3 TN and 31.4 mg/m^3 TP.

Estuary compartment	Freshwater fraction	TN (mg/m^3)	TP (mg/m^3)	Flushing time (days)	Macroalgal susceptibility	Phytoplankton susceptibility	ETI susceptibility
Upper estuary	68%	539	22	2.8	D	A	**D**
Lower estuary	17%	164	6	0.6	B	A	**B**

Under summer flow conditions, macroalgal susceptibility of the upper and lower estuary is unchanged (Bands D and B respectively) although potential TN concentrations move closer to the lower end of each band. With reduced flow, the flushing time of the upper estuary increases sufficiently to support phytoplankton growth. The model predicts a potential Chl-*a* concentration of 28 µg/l, which places the upper estuary in Band D – very high susceptibility to phytoplankton. The lower estuary is sufficiently well flushed by the sea that predicted Chl-*a* concentrations are < 5 µg/l (Band A).

Table 6-8: Results of dilution modelling using the two-compartment model for the Tokomairiro Estuary under summer flows. Calculations use river flow of 1.27 m^3/s, river inflow concentrations of 549 mg/m^3 TN and 50 mg/m^3 TP.

Mean river TN (mg/m^3)	Freshwater fraction	TN (mg/m^3)	TP (mg/m^3)	Flushing time (days)	Macroalgal susceptibility	Phytoplankton susceptibility	ETI susceptibility
Upper estuary	62%	354	34	4.5	D	D	**D**
Lower estuary	10%	93	12	0.6	B	A	**B**

Overall, the two-compartment model is consistent with the single compartment model, predicting that the estuary has a very high susceptibility to macroalgae, and a very high susceptibility to phytoplankton under summer conditions. The two-compartment model indicates that the upper estuary is more likely to be impacted by both macroalgal and phytoplankton blooms than the lower estuary, although the limited intertidal area of the upper estuary may restrict the extent over which macroalgal blooms occur.

7 Comparison of susceptibility metrics with observed estuarine state

The ecological qualities (Table 6-1) expected from SSRTRE type estuaries, like the Tokomairiro Estuary, that have a very high susceptibility to macroalgae (ETI Band D) are:

- Ecological communities (e.g., bird, fish, seagrass, and macroinvertebrates) that are strongly impacted by macroalgae.
- Persistent very high % macroalgal cover (>75%) and/or biomass (>1000 g/m2 wet weight), with entrainment in sediment.
- Sediment quality degraded with sulphidic conditions near the sediment surface.

The ecological qualities expected when SSRTRE type estuaries have a very high susceptibility to phytoplankton (ETI Band D) are:

- Excessive algal growth making ecological communities at high risk of undergoing a regime shift to a persistent, degraded state without macrophyte/seagrass cover.

Macroalgal EQR is one of the primary indicators of estuarine trophic condition used in the ETI tool 2 score (Zeldis, Whitehead et al. 2017). Recent broad-scale habitat mapping by Stevens (2018) assessed opportunistic macroalgal growth by mapping the spatial spread and density of macroalgae in available intertidal habitat in the Tokomairiro Estuary and calculating an "Ecological Quality Rating" (EQR) (Borja, Josefson et al. 2007). The estuary supported ca. 3% opportunistic macroalgal cover within the Available Intertidal Habitat (AIH), largely in the lower estuary near the entrance where the dominant species was the red alga *Gracilaria chilensis*. The green alga *Ulva spp.* was present in some sheltered parts of the middle estuary. The resulting EQR was 0.62. This gave an overall quality rating of 'good' (≥0.6 - <0.8), sitting near the boundary with 'intermediate' (≥0.4 - <0.6). Stevens (2018) noted that this rating reflects a situation where macroalgal growth is not widespread, but when it is present, it is entrained in sediment and therefore likely to be persistent.

Sampling of phytoplankton in surface waters throughout the estuary by Robertson and Robertson (2018) recorded low concentrations of phytoplankton (3-5 mg/m^3, an ETI rating of Band A - Low). However, samples taken from 2-3 m depth at two sites in the upper estuary contained very high chlorophyll *a* concentrations (40-41 mg/m^3, ETI Band D – 'Very high'). These contrasting results from surface and deeper waters are likely to be the result of stratified waters in the upper estuary, with buoyant fresh water trapping eutrophic high salinity waters on the bottom of the estuary (Robertson and Robertson 2018; Stevens 2018).

Sediment condition measured by Robertson and Robertson (2018) showed a combination of high muddiness and poor sediment oxygenation at sites in the mid to upper estuary. They observed an approximately 5 km stretch of the upper estuary bottom water and underlying sediment that was eutrophic at the time of sampling. Sites in the mid and upper estuary in their study had redox potential values in ETI Band D. In contrast, underlying sediments in the lower estuary had low organic carbon and nutrient contents and were relatively well oxygenated; the lower estuary sediments had redox potential values in ETI Band B throughout the depth profile sampled. Robertson and Robertson (2018) state that sediment conditions in the mid to upper estuary have resulted in 'macroinvertebrate community that would likely be dominated by mud and/or enrichment tolerant species'.

From the Stevens (2018) broad scale report that included fine scale monitoring results, the Tokomairiro Estuary had an overall ETI score of 0.59 and a risk indicator rating of 'moderate' (ETI Band C).

Both the field-measured trophic indicators (Robertson and Robertson 2018; Stevens 2018) and the dilution model-derived susceptibility metrics in the current report show varying impacts of nutrient loads on the upper and lower regions of the estuary. Also, the overall estuary ETI score derived from field measurements is lower than that calculated in this report based on loading and physical characteristics of the estuary. There are several potential causes for this latter difference.

1. The impact of loading is not equal across the estuary. Neither the simple box models used in this report to calculate an ETI score, nor the field measurements of Stevens (2018) and Robertson and Robertson (2018), attempt to resolve all of the spatial patterns of impact across the estuary.
2. Temporal patterns of impact.
    a. The monitoring conducted in Tokomairiro Estuary has recorded the state of the estuary at a few points in time. The modelling of susceptibility of the estuary to eutrophication in this report describes an average state. In nature, processes such as seasonal algal blooms, and flushing events can change estuary condition away from its average state.
    b. If nutrient and sediment loads have increased in the recent past, it is possible that the effects of these increases have not yet become apparent. Times between load increase and impact vary from estuary to estuary; in general, more high energy systems with coarse sediments, high flushing and high organic matter turnover (low storage) are both slower to degrade following increases in loading and quicker to improve given decreases in loading (Borja, Dauer et al. 2010).

The differences between observed estuarine state (Stevens 2018) and that predicted using dilution modelling under mean flow and mean annual 2014–18 total nitrogen loads (Table 6-4) can largely be addressed by using a two compartment model under summer flow and nutrient conditions (Table 6-8). In this two-compartment model, the upper estuary is more susceptible to both macroalgal and phytoplankton blooms.

8 Catchment load bandings

To aid management decisions, we present the catchment loadings to the estuary's terminal reaches for total nitrogen (TN) required to obtain an A, B, C or D band for macroalgal susceptibility based on the dilution modelling approach. These loading bands are derived from the potential TN concentration bandings presented in Table 6-1. ORC have requested that load band estimates are also made using Dissolved Inorganic Nitrogen (DIN), which represents the most bio-available forms of nitrogen. The observed ratio of DIN to TN in the Tokomairiro River at West Branch Bridge is 62%. This ratio used to convert TN bands to DIN.

As described previously, eutrophic state occurs along a continuum, and the thresholds between bands (Table 8-1) indicate transitional conditions rather than abrupt changes in estuary ecological health. Gradual shifts in eutrophic state will be seen as these thresholds are approached. With this in mind, the loading bands are intended as a guide to what catchment loads would be required to achieve various estuary eutrophic states.

Because the upper estuary shows the highest susceptibility to both macroalgal and phytoplankton blooms, the nutrient load bands are based on the predicted response of the upper estuary using the two-compartment model.

Table 8-1: Annual freshwater TN and DIN loads to the Tokomairiro Estuary required to meet each ETI tool 1 band of eutrophication susceptibility from macroalgal growth. Based on the Plew, Zeldis et al. (2019) CLUES-Estuary tool.

	Macroalgal banding			
	Band A	**Band B**	**Band C**	**Band D**
TN (kg/y)	<7,000	7,000-19,900	19,500-32,200	>32,000
DIN (kg/y)	<4,300	4,300-12,100	12,100-19,800	>19,800

Note that flow has an important influence on the load bands as it affects both the concentration of the inflow and the amount of dilution in the estuary. The load bandings in Table 8-1 will change if flow is increased or decreased from 2.239 m^3/s (the mean flow estimate: Table 2-3).

To manage or restrict phytoplankton blooms, focusing on nutrient concentrations rather than loads is likely to be more effective. Riverine nitrogen concentrations required to meet the different ETI bands for phytoplankton susceptibility under summer conditions can be obtained from Figure 8-1. The bandings are sensitive to inflow. As inflow decreases, dilution tends to increase but flushing times increase. The net effect that the nutrient concentrations corresponding to each ETI phytoplankton band increase at higher and lower flows (Figure 8-1).

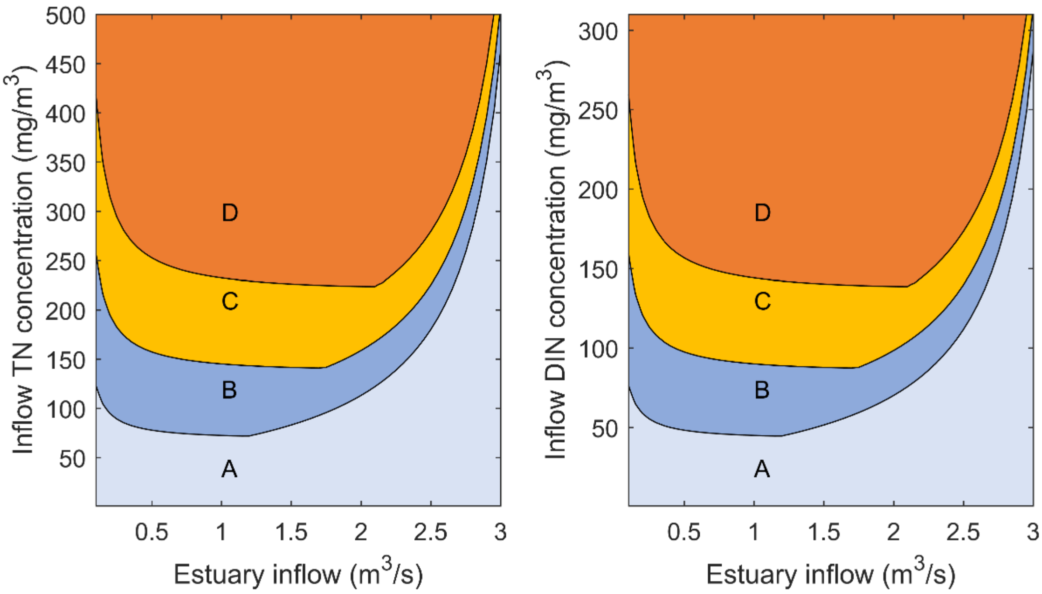

Figure 8-1: ETI phytoplankton susceptibility bands in the upper Tokomairiro Estuary as a function of flow and inflow nutrient concentrations. A ratio of DIN:TN = 0.62:1 is assumed, and the nitrogen to phosphorus ratio in the inflow is assumed to remain constant.

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