Eutrophication susceptibility assessment of Kaikorai Estuary

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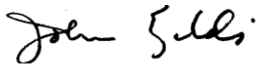	Reviewed by:	John Zeldis
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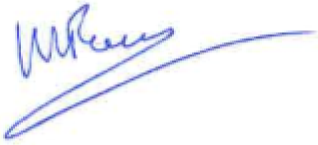	Approved for release by:	Helen Rouse

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Executive summary

Otago Regional Council (ORC) wishes to assess the susceptibility of the Kaikorai 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 give 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 Kaikorai Estuary during April/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 Kaikorai Estuary where there is low dilution of in-flowing river water with sea water.

Under current flow conditions, the ASSETS approach used in ETI tool 1 put the Kaikorai Estuary within the **moderate physical susceptibility** banding. The Kaikorai Estuary has a **moderate 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 'Moderate' N load susceptibility results in a **moderate combined physical and nutrient load susceptibility (Band B)**, according to the ASSETS approach.

Using the dilution modelling estimate of eutrophication susceptibility, the Kaikorai Estuary has an ETI susceptibility score in **Band D (very high) for susceptibility to eutrophication**.

Differences between trophic indicators previously measured in the estuaries and the modelled susceptibility metrics in this report show surprisingly low observed macroalgal growth in the Kaikorai Estuary considering current nutrient loads. However, field-measured phytoplankton and sediment conditions broadly agree with those for ETI susceptibility bandings.

To aid management decisions, we present the catchment loadings for total nitrogen (TN) required to obtain an A, B, C or D grade for eutrophication susceptibility in each estuary based on the dilution modelling approach.

1 Introduction

To gain an understanding of how future changes to freshwater volumes and nutrient flows may affect the ecological health of the Kaikorai Estuary, Otago Regional Council 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 grades for eutrophication susceptibility in the estuary based on the dilution modelling approach.

Freshwater flows to the Kaikorai Estuary are dominated by the Kaikorai Stream. Freshwater flows 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 Kaikorai Estuary to eutrophication based on the N-loading and flow information provided to NIWA, and the measured bathymetric characteristics of the estuary.

2 Flow and N-load calculations

Inflows to the Kaikorai Estuary are not monitored. We estimate inflows and loads to the Kaikorai Estuary using a combination of modelled estimates (Booker and Woods 2014) obtained from NZRiverMaps (https://shiny.niwa.co.nz/nzrivermaps/) and observed nutrient concentrations in the estuary. NZrivermaps is a web-based tool that provides modelled estimates (from statistical modelling) of a wide variety of parameters, including hydrological and water quality variables, across the entire New Zealand River Environment Classification (REC).

Modelled flow and median nutrient concentrations for the terminal reach of the Kaikorai Stream are given in Table 2-1. The modelled concentrations indicate that dissolved inorganic nitrogen (DIN: sum of nitrate and ammonium) consists mostly of nitrate (94%), and that DIN accounts for 76% of total nitrogen (TN: sum of dissolved and particulate nitrogen). Dissolved reactive phosphorus (DRP) accounts for 34% of total phosphorus (TP: sum of dissolved and particulate phosphorus). The modelled estimates do not include any point sources into the estuary or ground water infiltration.

Table 2-1: Modelled flow and nutrient concentrations for the freshwater inputs to the Kaikorai Estuary. Data were obtained from NZRiverMaps https://shiny.niwa.co.nz/nzrivermaps/.

Parameter	Value
Mean flow	0.447 m^3/s
Median flow	0.265 m^3/s
Mean annual low flow (MALF)	0.110 m^3/s
Total nitrogen	547 µg/l
Ammoniacal nitrogen	22.8 µg/l
Nitrate nitrogen	391 µg/l
Dissolved inorganic nitrogen	414 µg/l
Total phosphorus	55.5 µg/l
Dissolved reactive phosphorus	18.8 µg/l

Otago Regional Council (ORC) have monitored water quality in the Kaikorai Estuary at the Brighton Road bridge since August 1997. Nutrient and conductivity data for the last 5 years are plotted in Figure 2-1 and summarised in Table 2-2. Nitrogen in particular shows a seasonal cycle with higher winter-time concentrations than in summer. Based on the low conductivity values, these data were surface samples from a mostly freshwater layer (~1% sea water content). These nutrient concentrations likely represent the concentrations in the freshwater sources. The observed median DIN and TN concentrations (Table 2-2) are similar to the modelled values in Table 2-1, although the observed TP and DRP values are about 50% lower.

Table 2-2: Observed nutrient concentrations in the Kaikorai Estuary. Based on monthly surface samples collected at the Brighton Road bridge from May 2014 to April 2019. Data provided by Otago Regional Council.

Parameter	Mean concentration (mg/m^3)	Median concentration (mg/m^3)
Total Nitrogen	723	570
Dissolved inorganic nitrogen	468	355
Total phosphorus	29.7	24.0
Dissolved reactive phosphorus	10.6	9.6

We assume that annual loads to the estuary can be approximated by multiplying observed mean concentrations by modelled mean flow. Note that this approximation does not account for any relationship between flow and concentration, but in the absence of comparable flow and nutrient data from the Kaikorai Stream, we consider this the best available option for estimating annual loads. The estimated annual loads and mean inflow to the Kaikorai Estuary are summarised in Table 2-3.

Table 2-3: Estimated mean flows and mean annual loads to the Kaikorai Estuary. Mean annual loads are estimated from mean flows from https://shiny.niwa.co.nz/nzrivermaps/ and mean concentrations measured at the Brighton Road bridge from May 2014 - April 2019.

Mean inflow (m^3/s)	Total nitrogen (kg/y)	Dissolved inorganic nitrogen (kg/y)	Total phosphorus (kg/y)	Dissolved reactive phosphorus (kg/y)
0.447	10,200	6,600	420	150

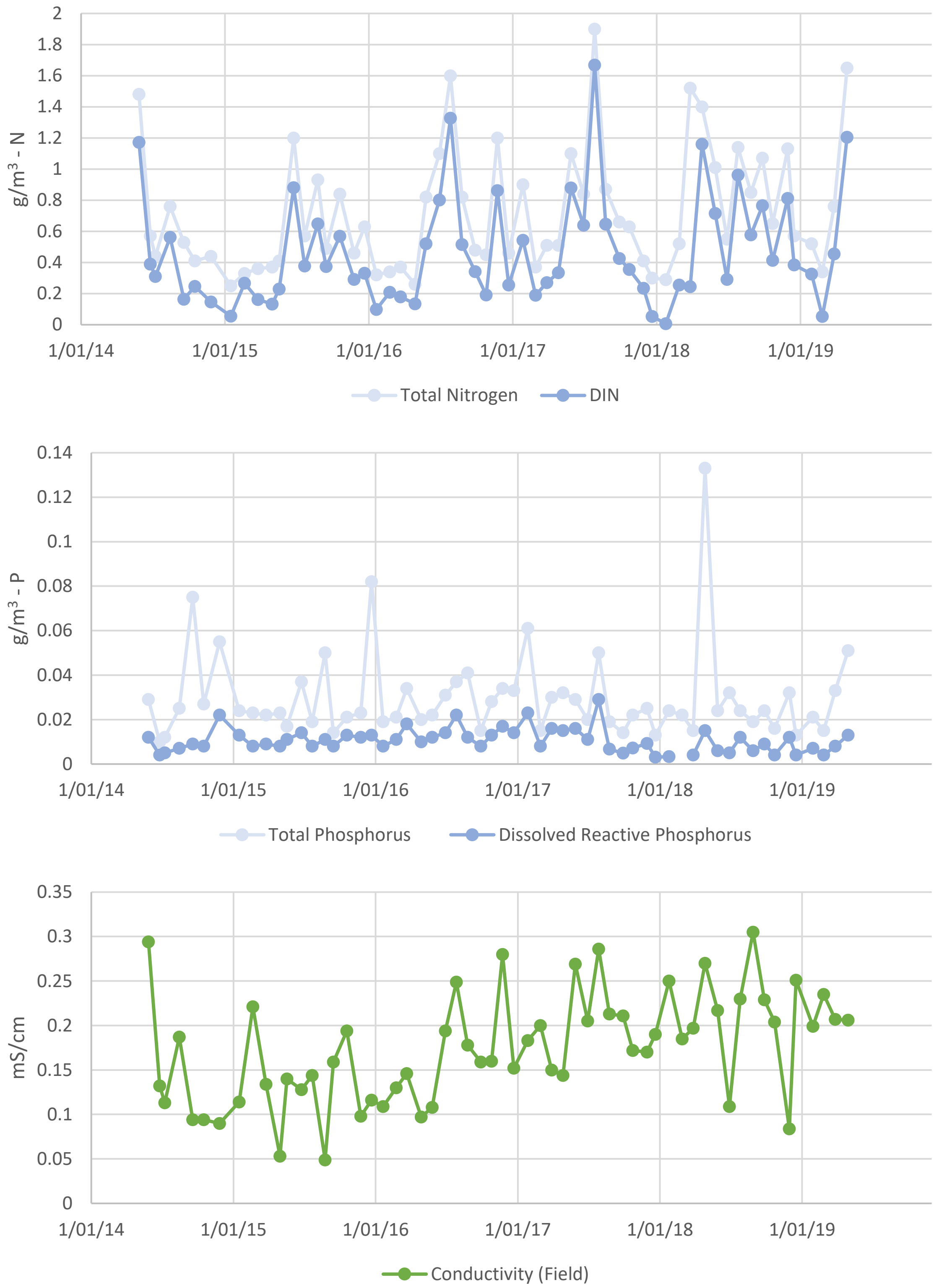

Figure 2-1: Nutrient and conductivity observations from the Kaikorai Estuary at Brighton Road bridge. Based on the low conductivities, these data appear to be surface samples with a high freshwater content.

3 Bathymetric surveys

Bathymetric surveys were conducted for the Kaikorai Estuary to obtain accurate estuary surface areas and volumes. A boat-mounted echosounder (Sonarmite) and RTK-GPS (real-time kinematic global positioning system) were used to obtain bed elevations over the navigable parts of the estuary on 28th April 2019 (Figure 3-1). The water level in the estuary was high (0.88 m NZVD2016) following recent rain, but large parts of the estuary could not be surveyed as a minimum depth of 0.35 m is required for the echosounder. The estuary water level dropped substantially over the next few days, and drone-based lidar unit (LIDAR USA Snoopy, Figure 3-1) was used to map the intertidal parts of the estuary near low tide on the 1st and 3rd May 2019. The estuary bathymetry is displayed in Figure 3-2.

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

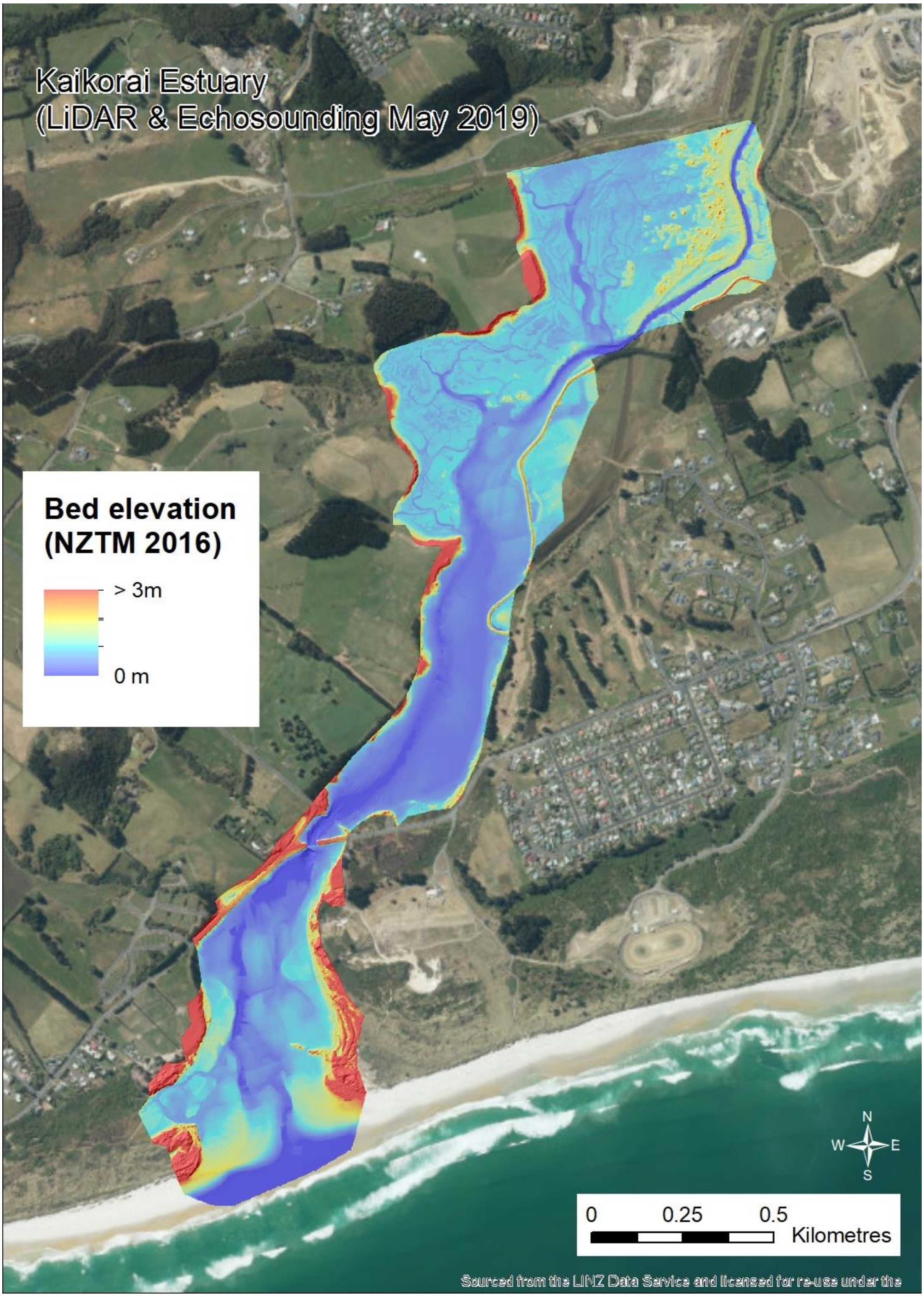

Figure 3-2: Surveyed bathymetry of the Kaikorai Estuary. Bathymetry data compiled from echo sounder survey conducted 28th April and drone based lidar on 1st and 3rd May 2019. Elevations are relative to NZVD 2016.

Profiles of salinities were made throughout the estuary near high tide on 3 May 2019, and are plotted as a vertical slice along the estuary and channel thalweg in Figure 3-3. We determined that the Kaikorai Estuary is influenced by salinity up to 2.3 km inland (profile K32 in Figure 3-4). However, Robertson and Robertson (2018) measured salinity in the Kaikorai Stream on 12 February 2018 and detected bottom water salinities as high as 13.5 ppt as far upstream as our site K26 (3.5 km in Figure 3-3). It is likely that the upper extend of salt water intrusion varies with freshwater inflow, tidal range and mouth opening. When mouth conditions and tidal range permit, salt water may penetrate up into the Kaikorai Stream, then become trapped by a shallow sill around the locations of sites K34-K32. Our measurements were taken after a period of rainfall that may have increased flows sufficiently to flush the bottom waters from the Kaikorai Stream. While the Kaikorai Stream is moderately deep (~ 1 m) compared to the estuary (mean depth ~0.41 m), it is narrow, and its volume small. Consequently, choosing how far up the stream the estuary extends has little effect on our susceptibility calculations. We have defined the upstream extent of the estuary to be approximately mid-way between where we detected salinity > 1 ppt and the upper-most site of Robertson and Robertson (2018). This point is 3.9 km from the estuary entrance (Figure 3-3), near the location of K28 in Figure 3-4. The extent of our estuary bathymetry is shown in Figure 3-2.

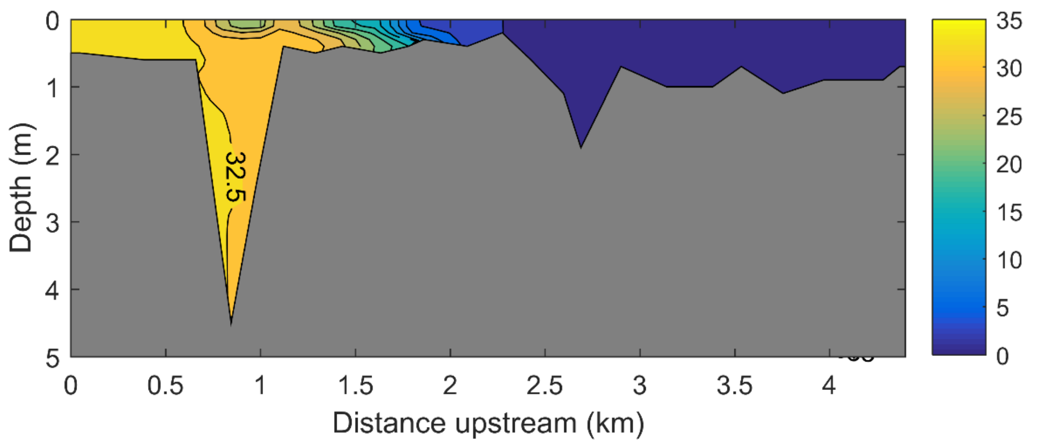

Figure 3-3: Profiles of salinity recorded along the length of the Kaikorai Estuary and Kaikorai Stream on 3 May 2019. Saline waters were detected up to 2.3 km upstream of the estuary mouth.

Figure 3-4: Locations of salinity profiles measured in the Kaikorai Estuary on 3 May 2019. Profiles were taken within 2 hrs of high tide, and saline influence (salinity >1 ppt) was detected as far upstream as site K32.

Estuary water level data were obtained by ORC using a temporary water level recorder installed on old bridge piles 100 m upstream of the Brighton Road bridge. Data were collected over the period 23 January 2019 to 11 March 2019. Raw water level data showed a downward drift of 561 mm relative to visual staff gauge readings over the deployment. A linear ramp correction was applied to the data by ORC. There is no way of determining if this drift occurred at a constant rate or at variable rates over the data collection period. The data with the linear ramp correction are shown in Figure 3-5. Water levels show a combination of tidal fluctuation superimposed on longer time-scale increases and decreases in water level. The longer time-scale fluctuations are driven by changes in the estuary mouth opening. When the mouth is constricted, tidal water level fluctuations are small (20-30 cm), while tidal ranges of ~80 cm occur when the mouth opening is wider. The mean (mid-tide) water level varies between 0 and 0.6 m above NZVD2016.

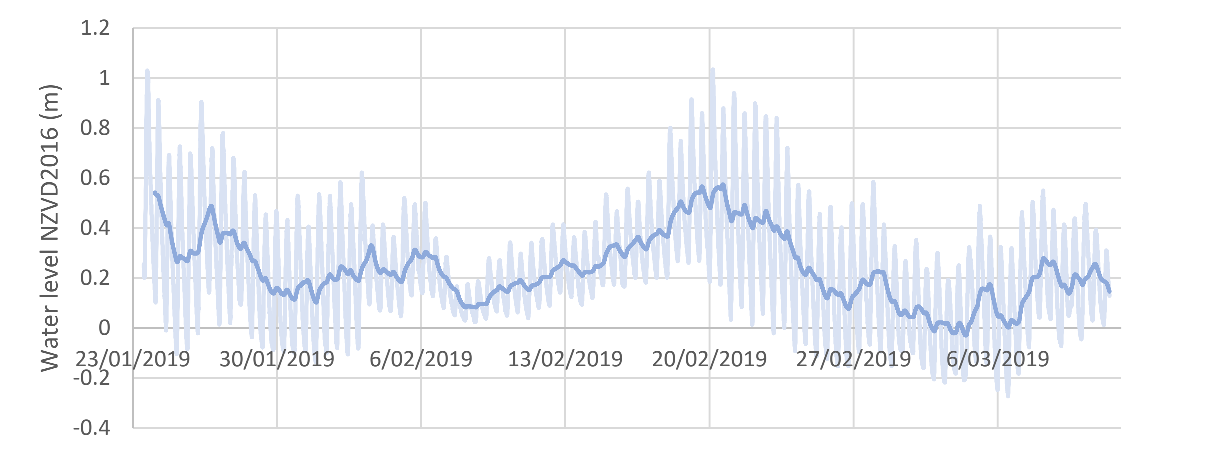

Figure 3-5: Water levels recorded in the Kaikorai Estuary from 23 Jan - 11 Mar 2019. The dark blue line shows a moving average which removes the tidal fluctuations. Data were recorded by ORC with a temporary recorder placed upstream of the road bridge. A linear adjustment has been applied to correct for a -561 mm calibration drift over the deployment.

The fluctuating mean water level and varying tidal range due to mouth constrictions make it difficult to define a spring high tide water level, as well as tidal prism.

For convenience, spring high tide was defined as the 95th percentile of high tide water levels (0.915 m), and spring tidal prism as the 95th percentile of the difference in volume between each high tide and the subsequent low tide. Percent intertidal area was defined as the difference in surface area covered at spring high tide and the area covered at the 5th percentile of levels at low water (-0.207 m). Surface areas, tidal range, volumes and surface areas are reported in Table 3-1.

Table 3-1: Physical properties of the Kaikorai 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)
759,050	97%	0.854	317,000	**293,525**	0.418

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 Kaikorai Estuary by physiographical type according to ETI tool 1.

Based on the data described in section 3, the estuary is classified as a Shallow Intertidal-dominated Estuary (SIDE), defined in ETI tool 1 as <3 m depth and intertidal area comprising >40 per cent of total estuary area. Eutrophication susceptibility calculations appropriate to this estuary type are applied in the following sections.

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 Kaikorai Estuary has a moderate tidal range (0.854 m). The mean daily inflow is 38,620 m^3/day and the estuary volume is 317,000 m^3. The flushing potential for the estuary is 0.121. 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 Kaikorai Estuary flushing potential is high.

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

Estuary	Mean annual freshwater input (m^3/day)	Estuary volume at spring high tide (m^3)	Flushing potential	Flushing potential band (ETI tool 1)
Kaikorai	38,620	317,000	0.121	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 Kaikorai Estuary is 8.9×10^{-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 Kaikorai 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 Kaikorai 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 et al. 2016b).

		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 Kaikorai 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).

Kaikorai Estuary has a loading of 37 mg/m^2/d, which indicates a moderate N-load susceptibility.

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

Estuary	Annual N-loads (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)
Kaikorai Estuary	10,200	0.759	37	Moderate (10-50 mg/m^2/day)

5.5 Combined physical and nutrient load susceptibility

Under the present flow and nutrient loading conditions, we assessed the Kaikorai Estuary as 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 **moderate combined physical and nutrient load susceptibility** (Band B) (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 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 ≤ 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 ≤ 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} ≥ 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

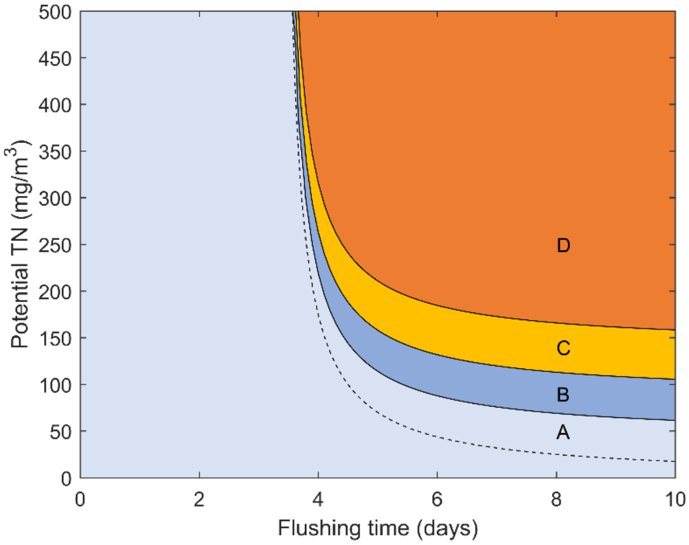

Figure 6-1: ETI susceptibility bandings for phytoplankton based on flushing time and potential total nitrogen concentrations. This graph shows model output based on an assumed half saturation coefficient of 35 mg/m^3 TN and a net specific growth rate of 0.3 day^{-1} when nitrogen is the limiting nutrient. The solid curves show the thresholds between bandings, and below the dashed line no phytoplankton growth will occur.

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 in the estuary averaged over time and space.

A modified tidal prism model (Luketina 1998) is used to calculate dilution for the Kaikorai 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

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

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).

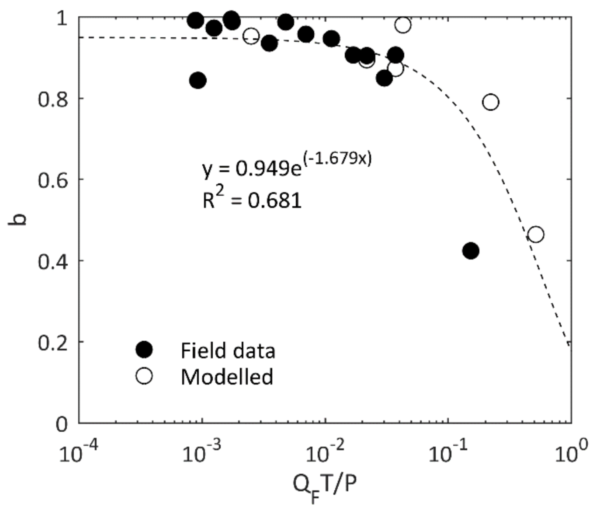

Figure 6-2: Variation of tuning factor (b) with increasing ratio of freshwater inflow to tidal prism. The data shown are from a range of different estuaries. From Plew, Zeldis et al. (2018).

6.2 Dilution modelling results

The dilution model for the Kaikorai Estuary is tuned using salinities, freshwater inflows and tidal prisms observed during the field survey. The inputs to, and results of, this tuning procedure are given in Table 6-2**Error! Reference source not found.**. Note that the reference tuning factor has a value > 1. This is a physically unrealistic value suggesting over 100% return flow from the ocean to the estuary. While this was not necessary in our calculations below, we recommend setting *b* to a maximum of 0.98.

Table 6-2: Calibration of the estuary mixing model.

Estuary	Tidal prism (m^3)	Freshwater inflow (m^3/s)	Mean salinity	Observed tuning parameter b	Reference tuning factor b_0
Kaikorai Estuary	143,410	0.090	20.28	0.979	1.026

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 Kaikorai has a very high susceptibility to eutrophication via macroalgal growth (ETI band D), but a low susceptibility to phytoplankton due to its short flushing time. However, stratification can occur in deep pockets within SIDEs, and local flushing times of these areas can 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 6-3: Results of dilution modelling for the Kaikorai Estuary under mean flow and mean annual (May 2014 – April 2019) total nitrogen loads. The estuary is classified as a Shallow Intertidally Dominated Estuary (SIDE), and as such the overall ETI susceptibility band is determined by the macroalgae susceptibility. Note that the estuary is treated as a single compartment, and inflows and loads are summed to estimate the inflow concentration.

Mean river TN concentration (mg/m^3)	Ocean TN concentration (mg/m^3)	Estuary freshwater fraction	Estuary TN (mg/m^3)	Estuary flushing time (days)	Macroalgae susceptibility	Phytoplankton susceptibility	ETI susceptibility
723	40	46%	353	1.7	D	A	**D**

At times, the mouth of the Kaikorai Estuary can constrict (Figure 6-3). During such periods, there may be a narrow channel by which the estuary drains to the sea, but there is no seawater input. The flushing time of the estuary may increase sufficiently that wide-spread phytoplankton blooms can occur. The salinity of the estuary will reduce over time as freshwater replaces brackish water, although deep pockets in the estuary will trap denser, high salinity water. Mouth closures are most common in summer low-flow periods. To estimate the likely phytoplankton response of the estuary during closure periods, we repeat the dilution modelling using mean annual low flow (0.110 m^3/s), and the mean summer (Dec-Feb, 2014-2019) nutrient concentrations. We calculate the potential nutrient concentrations and flushing times when the estuary is open and closed (Table 6-4).

Under summer flow conditions when the mouth is open, potential chlorophyll concentrations are predicted to reach 15 µg/l, which for meso/poly haline estuaries (salinity of 5-30 ppt) would be classified as a high susceptibility (Band C). When the mouth is closed, the flushing time increases to around 15 days, and the predicted potential chlorophyll concentrations increases to 23 µg/l. This chlorophyll level would place the Kaikorai Estuary in Band D for phytoplankton susceptibility.

The phytoplankton model includes phosphorus, and the molar ratio of N:P = 28:1 indicates that phytoplankton growth will likely be phosphorus limited.

Table 6-4: Phytoplankton susceptibilty of the Kaikorai Estuary under summer conditions. Modelling assumes mean annual low flow conditions but retains annual mean inflow nutrient concentrations. The estuary is modelled with the mouth open and closed to the sea.

Mouth state	Summer river TN (mg/m^3)	Summer river TP (mg/m^3)	Fresh water Inflow	Estuary freshwater fraction	Salinity	Estuary TN (mg/m^3)	Estuary TP (mg/m^3)	Estuary flushing time (days)	Predicted Chl-a (µg/l)	Phytoplankton susceptibility
Open	439	28	0.11	48%	18	233	18	7.3	15	C
Closed	439	28	0.11	100%	0	439	28	15.2	23	D

Because Shallow Intertidally Dominated Estuaries (SIDEs) are generally shallow and well mixed, phytoplankton blooms that do occur seldom trigger secondary expressions of eutrophication (such as low oxygen or severe light attenuation), and the overall ETI susceptibility is determined from the Macroalgae Susceptibility score. While we would expect this to be the case for Kaikorai estuary while the estuary mouth is open and the estuary is tidally flushed, under summer low flow conditions or periods of mouth closure, widespread phytoplankton blooms and associated secondary effects may occur.

Figure 6-3: Satellite image of the mouth of the Kaikorai Estuary on 8 March 2017. This image shows an an example of when the mouth of the estuary is closed and there is no sea water input. Image from GoogleEarth.

7 Comparison of susceptibility metrics with observed estuarine state

The ecological qualities (Table 6-1) expected from SIDE type estuaries, like Kaikorai Estuary, that have a high susceptibility to macroalgal eutrophication (Band D) are:

- Ecological communities (e.g., bird, fish, seagrass, and macroinvertebrates) that are strongly impacted by macroalgae
- Persistent very high % macroalgal cover (>50%) and/or biomass (>500 g/m^2 wet weight), with entrainment in sediment
- Sediment quality degraded with sulphidic conditons near the sediment surface.

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 Kaikorai Estuary and calculating an "Ecological Quality Rating" (EQR) (Borja, Josefson et al. 2007). The estuary supported <5% opportunistic macroalgal cover within the Available Intertidal Habitat (AIH). The resulting EQR was 0.9, corresponding to a Band B – 'Low' risk of adverse ecological impact. However, Stevens (2018) notes that recent sampling has found considerably higher macroalgal cover: Robertson and Robertson (2018) found 60-70% cover of intertidal macroalgae (*Ulva*) from one of their fine-scale monitoring sites in December 2017. Stevens (2018) suggests that a recent flood flow from the Kaikorai Stream may have removed macroalgal cover prior to his fine-scale monitoring, and that seasonal blooms of macroalgae are likely given the estuary's current trophic state.

The ecological qualities expected from estuaries that have a low susceptibility to phytoplankton eutrophication (Band A) are:

- Ecological communities that are healthy and resilient.

However, as described above, maintaining low susceptibility of this estuary to phytoplankton eutrophication is highly reliant on its flushing time being low, conditions that are expected when the mouth of the estuary is open. Because the ecological reports of Robertson and Robertson (2018), and Stevens (2018) show that the mouth of the estuary is restricted during periods of low flow, we also note that the ecological qualities expected from the estuary given prolonged periods of mouth closure (i.e., a very high susceptibility to phytoplankton eutrophication (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,

The 'fine-scale' monitoring study of Robertson and Robertson (2018) recorded chlorophyll *a* concentrations throughout the estuary surface water of 5-7mg/m^3 (an ETI rating of Band B - Moderate). However, they also observed that chlorophyll *a* concentrations increased with depth in the upper estuary, to 10-12mg/m^3 at 0.5m depth (ETI Band C - High) and 20-30mg/m^3 at depths greater than 1m (ETI Band D - Very High). Robertson and Robertson (2018) and Stevens (2018) observed that deeper waters in the upper estuary were stratified with buoyant fresh water trapping eutrophic high-salinity waters on the bottom of the estuary. Both reports suggest that phytoplankton blooms are likely in subtidal parts of the estuary at times when mouth of the estuary is constricted, increasing flushing times. Stevens (2018) notes that these conditions are likely to be worst during periods of low river flow during summer, and that such conditions can be expected to have a significant adverse effect on the biological health of the estuary.

Stevens (2018) identified a large area (17.2ha - 21%) of the total intertidal area as having depleted sediment oxygen, with an associated 'high' NZ ETI risk rating for the estuary. This was largely confined to soft and very soft muds located in the upper tidal range of the main settlement basin in the central estuary. This poor sediment oxygenation, combined with moderate to high risk indicator ratings associated with muddiness (Stevens 2018) are likely to have contributed to the'moderate to high stress on benthic macrofauna, resulting in a community tolerant of moderate organic enrichment and elevated muds' observed by Robertson and Robertson (2018). From the Stevens (2018) broad scale report that included fine scale monitoring results, the Kaikorai Estuary had an overall ETI score of 0.81 (ETI band D) reflecting a high degree of eutrophic symptoms. Comparison of field-measured trophic indicators (Robertson and Robertson 2018; Stevens 2018) and the dilution model-derived susceptibility metrics in the current report show a reasonably close match between the predicted and measured ecological states.

8 Catchment load bandings

To aid management decisions, we present the catchment loadings to the estuary's terminal river reaches for total nitrogen (TN) required to obtain an A, B, C or D grade for macroalgae 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 modelled nitrogen loads obtained from NZRiverMaps give DIN as 76% of TN, while the observed ratio is 65%. The observed ratio (65%) is used to convert TN bands to DIN.

As described previously, eutrophic state occurs along a continuum, and the thresholds between bands indicate transitional conditions rather than abrupt changes in estuary ecological health. Gradual shifts in trophic 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.

For the Kaikorai estuary, we use the single compartment dilution model, and assume mean flow conditions (Table 8-1).

Table 8-1: Annual freshwater TN and DIN loads to the Kaikorai 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.

	Macro-algal banding			
	Band A	Band B	Band C	Band D
TN (kg/y)	<1,800	1,800-5,500	5,500-9,150	>9,150
DIN (kg/y)	<1,150	1,150-3,550	3,550-5,950	>5,950

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 0.447 m^3/s (the mean flow estimate: Table 2-3).

Phytoplankton susceptibility under mean flow conditions will remain in the A band under all nitrogen loads because of the short flushing time. However, under summer low flow conditions, the inflow concentrations in Table 8-2 will be required to meet each ETI banding for phytoplankton (note that we have assumed the current N:P ratio in the inflow of 35:1 is maintained).

Table 8-2: Proposed inflow total nitrogen (TN) and dissolved inorganic nitrogen (DIN) concentrations required to meet ETI bands for phytoplankton under summer low flows when the mouth is open or closed. The calculations assume a summer low flow of 0.11 m^3/s.

		Phytoplankton banding			
Mouth State	**Nutrient**	**Band A**	**Band B**	**Band C**	**Band D**
Open	TN (mg/m^3)	<110	110-200	200-350	>350
	DIN (mg/m^3)	<70	70-130	130-230	>230
Closed	TN (mg/m^3)	<70	70-140	140-220	>220
	DIN (mg/m^3)	<45	45-90	90-140	>140

9 References

Atkinson, M.J., Smith, S.V. (1983) C:N:P ratios of benthic marine plants. *Limnology and Oceanography*, 28(3): 568-574. doi:10.4319/lo.1983.28.3.0568

Booker, D.J., Woods, R.A. (2014) Comparing and combining physically-based and empirically-based approaches for estimating the hydrology of ungauged catchments. *Journal of Hydrology*, 508: 227-239.

Borja, A., Josefson, A.B., Miles, A., Muxika, I., Olsgard, F., Phillips, G., Rodríguez, J.G., Rygg, B. (2007) An approach to the intercalibration of benthic ecological status assessment in the North Atlantic ecoregion, according to the European Water Framework Directive. *Marine Pollution Bulletin*, 55(1): 42-52. https://doi.org/10.1016/j.marpolbul.2006.08.018

Howarth, R.W., Marino, R. (2006) Nitrogen as the limiting nutrient for eutrophication in coastal marine ecosystems: Evolving views over three decades. *Limnology and Oceanography*, 51(1part2): 364-376. 10.4319/lo.2006.51.1_part_2.0364

Larned, S.T., Snelder, T., Unwin, M.J., McBride, G.B. (2016) Water quality in New Zealand rivers: current state and trends. *New Zealand Journal of Marine and Freshwater Research*: 1-29. 10.1080/00288330.2016.1150309

Luketina, D. (1998) Simple Tidal Prism Models Revisited. *Estuarine, Coastal and Shelf Science*, 46(1): 77-84. http://dx.doi.org/10.1006/ecss.1997.0235

Plew, D.R., Zeldis, J.R., Dudley, B.D., Whitehead, A.L., Stevens, L.M., Robertson, B.M., Robertson, B.P. (2019) Assessing the eutrophic susceptibility of New Zealand Estuaries. *Estuaries and Coasts*, submitted.

Plew, D.R., Zeldis, J.R., Shankar, U., Elliott, A.H. (2018) Using simple dilution models to predict New Zealand estuarine water quality. *Estuaries and Coasts*, 41(6): 1643-1659. 10.1007/s12237-018-0387-6

Robertson, B.M., Stevens, L., Robertson, B., Zeldis, J., Green, M., Madarasz-Smith, A., Plew, D., Storey, R., Hume, T., Oliver, M. (2016a) NZ Estuary Trophic Index Screening Tool 1. Determining eutrophication susceptibility using physical and nutrient load data. *Prepared for Environlink Tools Project: Estuarine Trophic Index*: 47. http://envirolink.govt.nz/assets/Envirolink-reports/R10-120NZ20Estuary20trophic20index20Screening20Tool20120-20Determining20eutrophication20susceptibility20using20physical20and20nutrient20load20data.PDF

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

Robertson, B.P., Robertson, B.M. (2018) Kaikorai Estuary: Fine Scale Monitoring 2017/18: 37.

Stevens, L.M. (2018) Kaikorai Estuary: Broad Scale Habitat Mapping 2018. Report prepared by Wriggle Coastal Management for Otago Regional Council. 30p. .

Zeldis, J., Plew, D., Whitehead, A., Madarasz-Smith, A., Oliver, M., Stevens, L., Robertson, B., Burge, O., Dudley, B. (2017) The New Zealand Estuary Trophic Index (ETI) Tools: Tool 1 - Determining

Eutrophication Susceptibility using Physical and Nutrient Load Data. Ministry of Business, Innovation and Employment Envirolink Tools: C01X1420. https://shiny.niwa.co.nz/Estuaries-Screening-Tool-1/

Zeldis, J., Whitehead, A., Plew, D., Madarasz-Smith, A., Oliver, M., Stevens, L., Robertson, B., Storey, R., Burge, O., Dudley, B. (2017) The New Zealand Estuary Trophic Index (ETI) Tools: Tool 2 - Assessing Estuary Trophic State using Measured Trophic Indicators: Ministry of Business, Innovation and Employment Envirolink Tools Contract: C01X1420. https://shiny.niwa.co.nz/Estuaries-Screening-Tool-2/