Eutrophication susceptibility assessment of Pounawea (Catlins) Estuary and Shag River Estuary

Prepared for Otago Regional Council

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Prepared by:
David Plew
Bruce Dudley

For any information regarding this report please contact:

David Plew
Hydrodynamics Scientist
Hydrodynamics
+64-3-343 7801
david.plew@niwa.co.nz

National Institute of Water & Atmospheric Research Ltd
PO Box 8602
Riccarton
Christchurch 8011

Phone +64 3 348 8987

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Executive summary

Otago Regional Council (ORC) wishes to understand the susceptibility of the Shag River Estuary and Pounawea (Catlins) Estuary to nutrient loading to understand the trophic conditions likely to result from nutrient loads specified in the Regional Water Plan. ORC commissioned NIWA to calculate the eutrophication susceptibility of these two estuaries according to the recently released Envirolink screening tool 1 for the New Zealand Estuary Trophic Index (ETI) (Robertson et al. 2016a, Zeldis et al. 2017a). NIWA was also asked to give nutrient loads to these estuaries that correspond to each of the four ETI trophic condition bands. River water quality and flow data for this work was provided by ORC.

Bathymetric surveys were conducted for the Shag River Estuary and Catlins Estuary during March and April 2018 to obtain accurate estuary surface areas and volumes for eutrophication susceptibility calculations.

We calculated eutrophication susceptibility of these two estuaries using two comparable ETI methods: the 'ASSETS' approach (Robertson et al. 2016), and the 'dilution modelling' approach (also called the CLUES-Estuary approach) (Plew, Zeldis et al. 2018). The latter approach is considered more appropriate for estuaries like the Shag River Estuary and Catlins Estuary with low dilution of in-flowing river water

Under current flow conditions, the ASSETS approach used in ETI tool 1 put the Catlins Estuary and Shag River Estuary within the **moderate physical susceptibility** banding. The Catlins Estuary and Shag River Estuary have 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)**, for both estuaries according to the ASSETS approach.

Using the dilution modelling estimate of eutrophication susceptibility, both the Shag River Estuary and Catlins Estuary had an ETI susceptibility score in **Band C (High) for susceptibility to eutrophication**.

A single compartment dilution model may overestimate the eutrophication susceptibility of the Catlins Estuary. The Owaka River provides 60% of the annual TN load to the estuary, but joins the estuary close to the sea. It is unlikely to have a strong influence on the upper part of the estuary above the Hina Hina Rd bridge. Hence, we also used a two-compartment model to separately assess the susceptibility of the upper (Catlins Lake) and lower Catlins Estuary. Using this approach, the Catlins Lake section of the estuary retained an ETI susceptibility score in **Band C (High) for susceptibility to eutrophication**, while the lower Catlins Estuary had an ETI susceptibility score in **Band B (Moderate) 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 both the Shag River Estuary and greater Catlins Estuary considering current nutrient loads. However, field-measured 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 Pounawea (Catlins) Estuary and Shag River Estuary, Otago Regional Council requested that NIWA determines eutrophication susceptibility of these estuaries using Envirolink screening tool 1 for the New Zealand Estuary Trophic Index (Robertson et al. 2016) (ETI tool 1).

This work includes:

- Determination of estuary type for both estuaries according to ETI tool 1;
- Application of ETI tool 1 methods for current flow and nitrogen (N) loading conditions;
- A bathymetric survey of each estuary to measure estuary volume and area;
- Determination of the flushing and dilution potential of each 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 each estuary for each scenario according to the ASSETS approach;
- Calculation of estuary areal N loads for each 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 each estuary, according to the ASSETS 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 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;
- Brief narrative guidance on the ecological condition that corresponded to the modelled susceptibility scores for each 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 each estuary based on the dilution modelling approach.

The main sources of freshwater flow and nutrients for the Catlins Estuary are Catlins River and Owaka River, while freshwater flows to the Shag River Estuary are dominated by the Shag River. Both freshwater flows from rivers and the nutrient loads they carry are heavily dependent on land use within catchments (Larned et al. 2015). 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 in 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 Catlins Estuary and Shag River Estuary to eutrophication based on the N-loading and flow information provided to NIWA, and the bathymetric characteristics of these estuaries.

2 Flow and N-load calculations

Estuary N loads were calculated from terminal reach nutrient loads (Shag River, Catlins River and Owaka River) and flows provided to NIWA by ORC.

Otago Regional Council provided 24 years of flow and nutrient data for the Shag River. Total nitrogen (TN) loads were highly variable (Figure 2-1), and strongly related to river flow (high loads occurring in years with high mean flows). While there has been a small (0.792 T/yr) increase in loads over the last 24 years, this increase is not statistically significant (P = 0.596). Mean TN concentrations have also increased slowly (0.0109 g/m^3/yr, Figure 2-2), but again this trend is not statistically significant (P = 0.204).

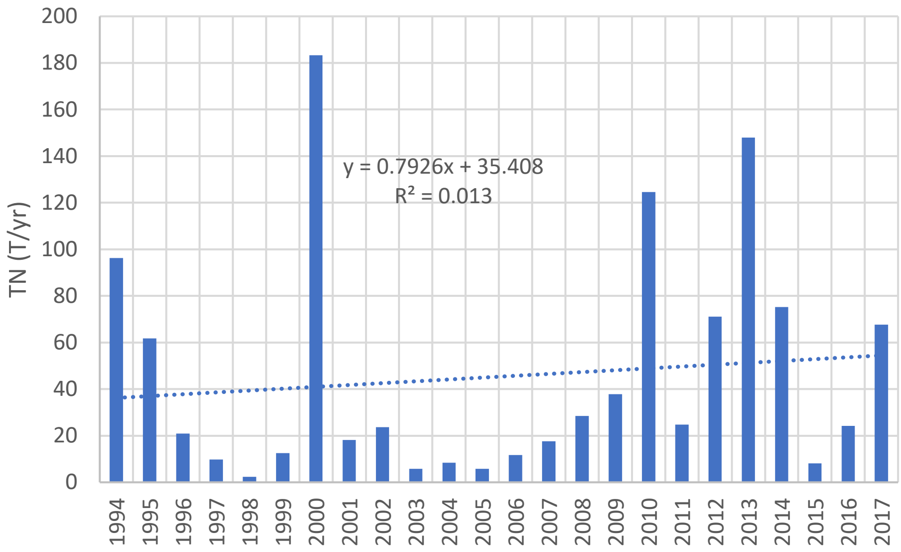

Figure 2-1: Annual mean total nitrogen loads from the Shag River. Annual loads calculated from daily mean flows @ Craig Rd and TN concentrations interpolated from nutrient samples @ Goodwood pump.

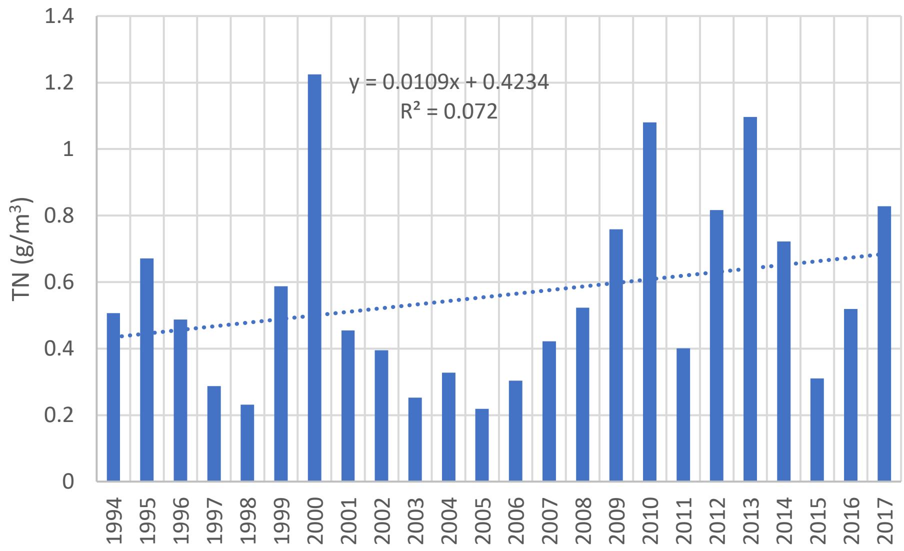

Figure 2-2: Annual mean total nitrogen concentrations in the Shag River as measured at Goodwood pump monitoring site.

Otago Regional Council provided 20 years of flow and nutrient data for the Catlins River and 4 years of similar data for the Owaka River. TN loads from the Catlins River have been slowly increasing over the last 20 years at a rate of approximately 2.3 T/yr (Figure 2-3). This increase is statistically significant ($P = 0.0096$). However, the highest annual load occurred in 2014, and has decreased since that point. Flows have not changed significantly over this period, so the change in load is mostly due to increasing TN concentrations in the Catlins River (Figure 2-4). The increase of 0.017 mg/m^3/yr is statistically significant ($P < 0.0001$).

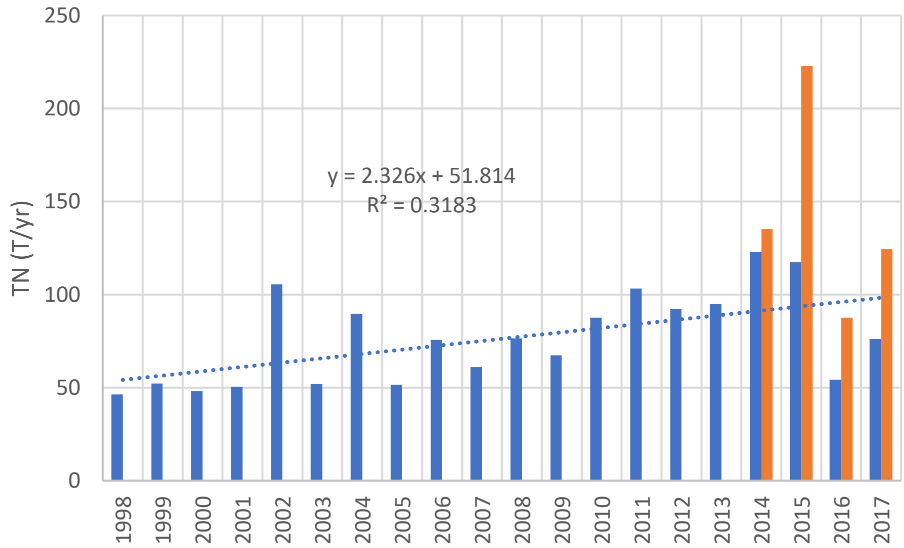

Figure 2-3: Annual total nitrogen loads from the Catlins River (blue) and Owaka River (red). Loads from the Catlins River calculated from daily flows and nutrient concentrations measured at Houipapa. Owaka River loads are calculated from daily flows and nutrient samples at Katea Road.

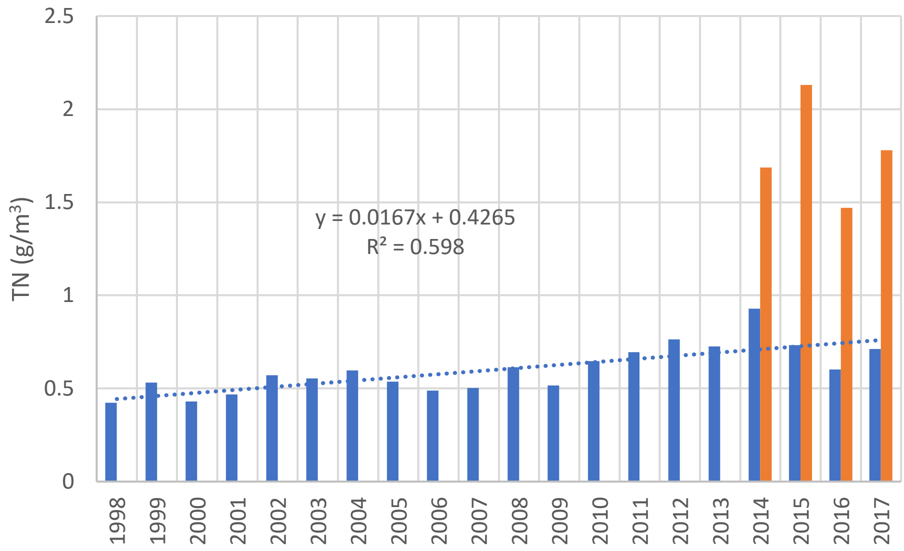

Figure 2-4: Mean annual total nitrogen concentrations in the Catlins River (blue) and Owaka River (red). Concentrations calculated from samples from Catlins@Houipapa and Owaka@Katea Rd.

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 et al. 2016, Dudley et al. 2017).

Table 2-1: Mean flows and mean annual loads for the inflows to the Catlins Estuary and the Shag River Estuary. Mean annual loads are averaged over 2013-17.

River	Mean flow (m^3/s)	TN load (T/yr)
Shag River	2.494	64.6
Catlins River	3.937	93.1
Owaka River	2.491	142.5
Catlins – combined	**6.375**	**235.6**

3 Bathymetric surveys

Bathymetric surveys were conducted for the Shag River Estuary and Catlins Estuary to obtain accurate estuary surface areas and volumes.

The Shag River Estuary was surveyed 16–17 April 2018 using a jet boat and a RiverPro ADCP (acoustic doppler current profiler) to measure depths. RTK-GPS (real-time kinematic global positioning system) was used to obtain position and elevations. LIDAR data collected 15 March 2017 (provided by Otago Regional Council) were used to obtain surface elevations over areas that could not be surveyed by boat. The LIDAR data were not collected at low tide, so some interpolation was required to estimate bed elevations over intertidal areas, particularly in the south-eastern portion of the estuary. Based on salinities measured at high tide on 17 April 2018, we determined that the Shag River is influenced by salinity as far inland as the bridge at SH1. This defines the upper extent of the estuary in our analysis. The estuary bathymetry is displayed in Figure 3-1.

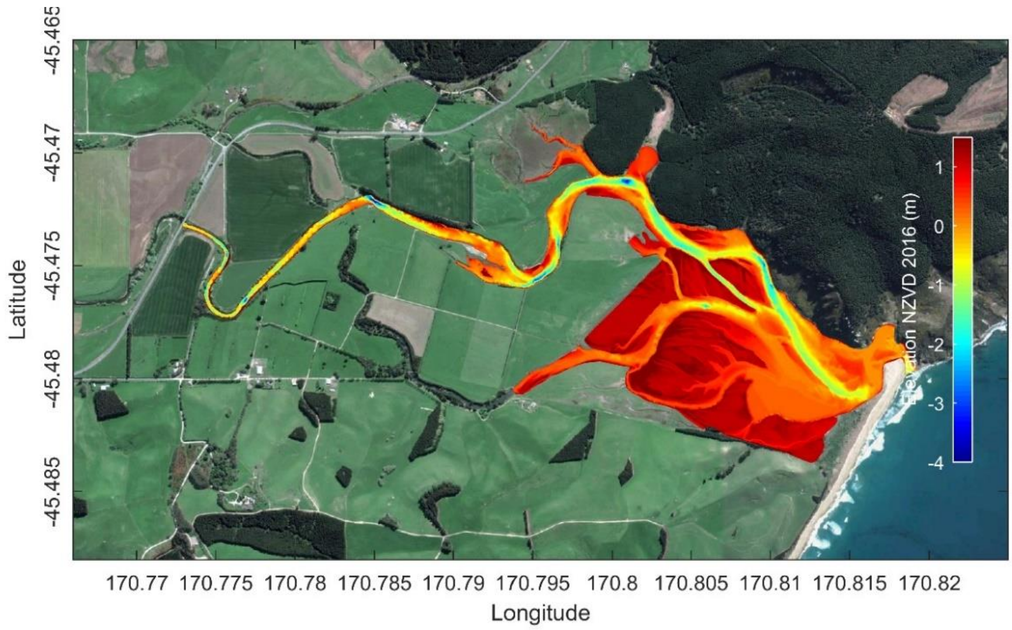

Figure 3-1: Surveyed bathymetry of the Shag River Estuary. Bathymetry data compiled from surveys conducted 16–17 April 2018 and LIDAR data from 15 March 2017. Elevations are relative to NZVD 2016.

Water level data obtained by ORC over the period 31 January 2018 to 16 April 2018 were used to obtain high tide volumes, tidal prisms, and intertidal area. As the estuary water levels were influenced by high river flows, we calculated tidal ranges using data collected when river flow was less than 5 m^3/s. Surface areas, tidal range, volumes and surface areas are reported in Table 3-1.

The Catlins Estuary was surveyed over the period 27–29 March 2018 by jet boat. Depths were measured using a SonarMite echo sounder, with horizontal and vertical position obtained using RTK-GPS. Survey data were referenced to local benchmarks, and elevations corrected to New Zealand Vertical Datum 2016 (NZVD 2016). LIDAR data provided by Otago Regional Council were used to obtain elevations of intertidal areas in the lower estuary. The bathymetry of the Catlins Estuary is shown in Figure 3-2.

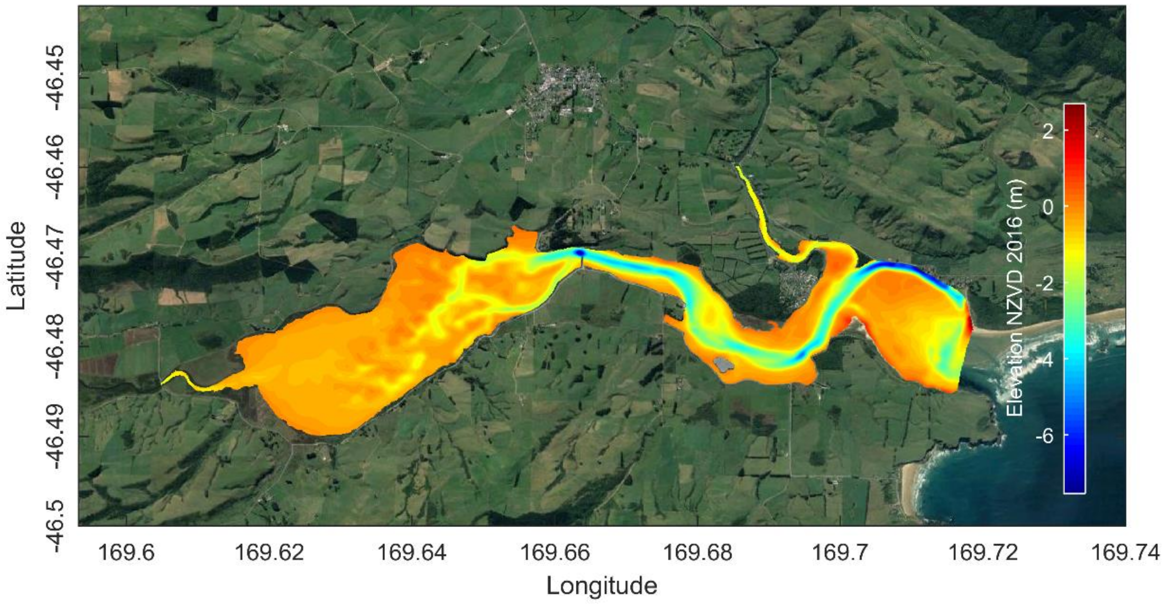

Figure 3-2: Surveyed bathymetry of the Catlins River Estuary. Bathymetry data compiled from surveys conducted 27–29 March 2018, and LIDAR data from 6–11 September 2004. Elevations are relative to NZVD 2016.

To determine volumes, areas and tidal prism at spring tide, we estimated spring high tide as the 96th percentile[1] of observed high tide water levels from water level data recorded at the Hina Hina Rd bridge from 31 Jan 2018 to 28 Mar 2018 (provided by Otago Regional Council).

There is a natural division of the Catlins Estuary at the Hina Hina Rd bridge, where the causeway constricts the estuary to a narrow channel beneath the bridge. We use the bridge to separate the upper (Catlins Lake) and lower parts of the estuary. Tidal prisms, volumes and surface areas of the upper and lower estuary, and the whole estuary, are reported in Table 3-1.

Table 3-1: Physical properties of the Shag River Estuary and Catlins Estuary. The Catlins Estuary is divided into upper and lower compartments at the Hina Hina Rd Bridge. NA = not applicable.

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)
Shag River Estuary	**1,223,500**	**67.5%**	**1.347**	**1,352,800**	**1,117,500**	**1.11**
Catlins Lake	4,413,600	86.6%	NA	6,479,100	6,136,700	1.47
Lower Catlins	3,715,300	57.1%	NA	7,677,200	5,626,900	2.07
Catlins - combined	**8,128,900**	**73.1%**	**1.863**	**14,156,300**	**11,763,600**	**1.74**

[1] Mean High Water Spring is defined as the average of the high tides on the days of spring tides. Over a 29.5 day lunar month, there are 57 tidal periods and 2 spring-neap cycles. Therefore, the highest 4/57 = 7% of tides are considered to be spring high tides. Mean High Water Spring is taken as the average of the highest 7% tides, which we approximate as the 96th percentile.

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 Shag River and Catlins estuaries by physiographical type according to ETI tool 1.

Based on these data, both estuaries are classified as Shallow Intertidal-dominated Estuaries (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 Shag River Estuary has a moderate tidal range (1.49 m). The mean daily inflow is 2.16×10^5 m^3/day and the estuary volume is 1,352,500 m^3. The flushing potential for the estuary is 0.16. 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 Shag River Estuary flushing potential is high.

The Catlins Estuary has a macro tidal range, total mean annual flow into the estuary in the range of 5.1×10^5 m^3/day, and an estuary volume of 14,156,300 m^3. This gives a flushing potential of 0.04 (Table 5-1). Comparison with the ETI bandings of flushing potentials for macro-tidal estuaries (high: $10^0 – 10^{-2}$; moderate: $10^{-3}–10^{-4}$) shows that the Catlins Estuary flushing potential is high.

Table 5-1: Calculated flushing potentials for the Catlins River and Shag River estuaries. Based on Robertson et al. (2016) Estuarine Trophic Index tool 1.

Estuary	Mean annual freshwater input (m^3/day)	Estuary volume at spring high tide (m^3)	Flushing potential	Flushing potential band (ETI tool 1)
Catlins	5.508×10^5	14,156,300	0.04	High
Shag River	2.155×10^5	1,352,800	0.16	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 Shag River Estuary is 2.1×10^{-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 Shag River Estuary. Thus, in the absence of defined dilution potential bandings for small estuaries, we define this estuary as having low dilution potentials.

The Catlin Estuary's dilution potential value is 2.0×10^{-9}. This places this estuary in the low band ($10^{-10}–10^{-9}$) for dilution potential.

5.3 Physical susceptibility

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

Catlins Estuary also has a high flushing potential and low dilution potential, identifying the estuary as moderately physical susceptible.

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 Shag River 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).

Shag River Estuary had a loading of 145 $mg/m^2/d$, which indicates a high N-load susceptibility.

Catlins Estuary has a present day loading of 79 $mg/m^2/d$, which also indicates high N-load susceptibility, according to the ASSETS approach.

Table 5-3: Areal N-load susceptibility for estuaries under current N loads. Based on Robertson et al. (2016) 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)
Shag River Estuary	64,600	1.224	145	High (50–250 $mg/m^2/day$)
Catlins Estuary	235,600	8.129	79	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 Shag River 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).

Catlins Estuary was assessed as having a moderate physical susceptibility, and a high N load susceptibility. According to the ASSETS approach, this combination results in a **high combined physical and nutrient load susceptibility** (Band C).

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

		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 et al. 2016, 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. 2017a) (Table 6-1).

The dilution modelling approach predicts the average potential total nitrogen (TN) concentration 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. Thus, potential nutrient concentrations are a stronger indicator of eutrophication susceptibility than observed values (Plew, Zeldis et al. 2018).

The ETI gives the following TN concentration bandings for susceptibility to eutrophication due to opportunistic macroalgae blooms:

- A: < 55 mg/m^3.
- B: 55 mg/m^3 – 110 mg/m^3.
- C: 110 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 TN concentrations with observations of opportunistic macroalgal from over 20 New Zealand estuaries (Plew, Zeldis et al. in prep). Observations of macroalgae impact were taken in summertime, while the potential TN 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 macroalgae 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).

Susceptibility to phytoplankton blooms are determined from potential TN concentration and flushing time using a growth model (Figure 6-1). The growth model is used to estimate the chlorophyll-a concentration, which related to a susceptibility band as reported in Table 6-1. The growth model shows that estuaries with short flushing times (<2.5 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. (in prep).

Band	A Minimal eutrophication	B Moderate eutrophication	C High eutrophication	D Very high eutrophication
Opportunistic Macroalgae	TN_{est} < 55 mg/m³ Ecological communities (e.g., bird, fish, seagrass, and macroinvertebrates) are healthy and resilient. Algal cover <5% and low biomass (<50 g/m² wet weight) of opportunistic macroalgal blooms and with no growth of algae in the underlying sediment. Sediment quality high	55 ≤ TN_{est} < 110 mg/m³ 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 (50–200 g/m² wet weight) of opportunistic macroalgal blooms and with no growth of algae in the underlying sediment. Sediment quality transitional	110 ≤ TN_{est} < 320 mg/m³ 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 (>200–1000 g/m² wet weight), often with entrainment in sediment. Sediment quality degraded	TN_{est} ≥ 320 mg/m³ Ecological communities (e.g., bird, fish, seagrass, and macroinvertebrates) 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
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

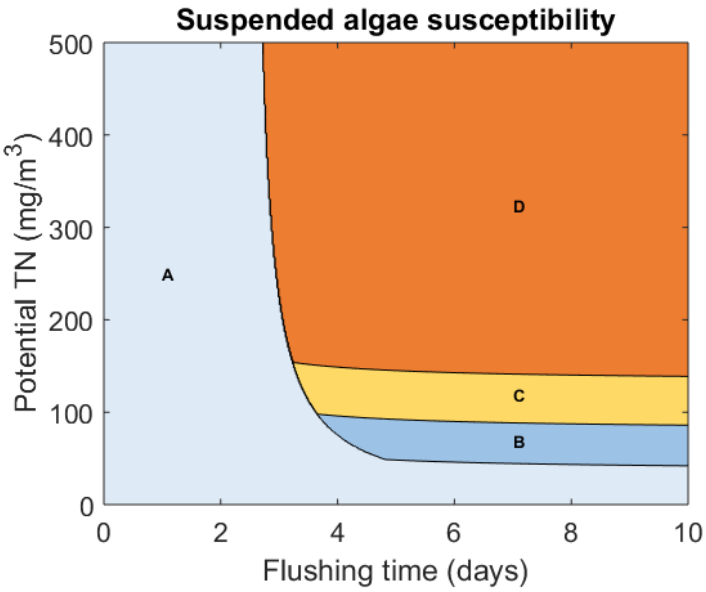

Figure 6-1: ETI susceptibility bandings for phytoplankton based on flushing time and potential total nitrogen concentrations. This graph shows model output based on an assumed half saturation coefficient of 45 mg/m^3 TN and a net specific growth rate of 0.4 day^{-1}.

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 Catlins Estuary and Shag River Estuary. The equations that describe the mixing model are given in Appendix A. 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 for 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), and is obtained by rearranging equation (1).

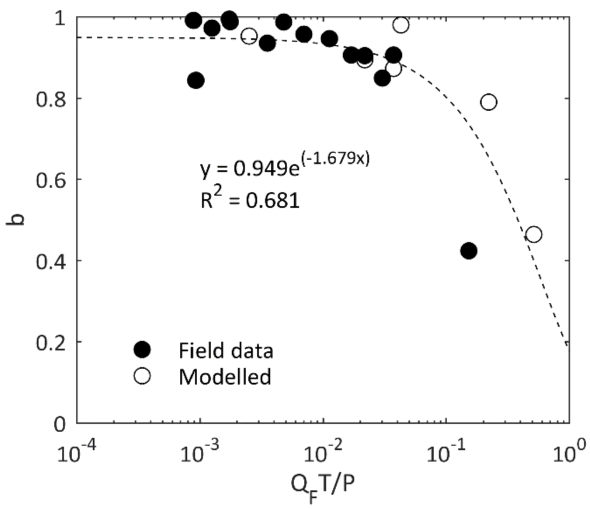

Figure 6-2: Variation of tuning factor with increasing ratio of freshwater inflow to tidal prism. The data shown are from a range of different estuaries. From Plew et al. (2018).

The Catlins Estuary has two distinct components, the upper estuary (Catlins Lake) and lower estuary. To better take account of the morphology of this estuary, we apply a modified tidal prism model that treats the estuary as two interconnected components. The upper compartment receives freshwater inflow from the Catlins River, and has tidal exchange (including a return flow) with the lower estuary. The lower estuary receives freshwater flow from the Owaka River, and has tidal exchange with both the ocean and upper estuary. For brevity, we omit a full description of the two-compartment model, but the equations that describe the model are given in Appendix A.

6.2 Dilution modelling results

The models for both estuaries are tuned using salinities, freshwater inflows and tidal prisms observed during the field surveys. The inputs to, and results of, this tuning procedure are given in Table 6-2.

Table 6-2: Calibration of the single compartment estuary mixing models.

Estuary	Tidal prism (m^3)	Freshwater inflow (m^3/s)	Mean salinity	Observed tuning parameter b	Reference tuning factor b_0
Shag River Estuary	755,500	2.00	30.2076	0.135	0.164
Catlins River Estuary	10,962,000	1.014	32.9945	0.916	0.922

Susceptibility assessments are conducted using mean annual loads and mean flows (see Table 2-1). For the single compartment dilution model, loads and flows into an estuary are added, and treated as a single combined source.

The single compartment dilution model indicates that the Shag River has a high susceptibility to macroalgae (ETI band C), but a low susceptibility to phytoplankton due to its short flushing time. Shallow Intertidally Dominated Estuaries (SIDEs) are generally shallow and well mixed. Phytoplankton blooms seldom trigger secondary expressions of eutrophication (such as low oxygen or severe light attenuation) in SIDEs, and the overall ETI Susceptibility is determined from the Macroalgae Susceptibility score.

The model predicts that the Catlins River Estuary has a high susceptibility to both macroalgae (ETI band C) and very high susceptibility to phytoplankton (ETI band D). The overall susceptibility score is C (high). The very high phytoplankton banding indicates that high chlorophyll concentrations or discolouration may be observed on occasions, but it is unlikely that this will trigger secondary symptoms of eutrophication, because as noted above, phytoplankton blooms seldom trigger secondary expressions of eutrophication (such as low oxygen or severe light attenuation) in SIDEs.

Table 6-3: Results of dilution modelling for the Shag River Estuary and Catlins Estuary under mean flow and mean annual 2013–17 total nitrogen loads. Both estuaries are classified as Shallow Intertidally Dominated Estuaries (SIDEs), and as such the overall ETI susceptibility band is determined by the macroalgae susceptibility. Note that estuaries are treated as a single compartment, and inflows and loads are summed to estimate the inflow concentration.

Estuary	Mean river concentration (mg/m³)	Ocean TN concentration (mg/m³)	Estuary freshwater fraction	Estuary TN (mg/m³)	Estuary flushing time (days)	Macroalgae susceptibility	Phytoplankton susceptibility	ETI susceptibility
Shag	821	40	11%	125	0.68	C	A	**C**
Catlins	1170	40	18%	240	5.8	C	D	**C**

The single compartment dilution model may overestimate the susceptibility of the Catlins estuary. The Owaka River provides 60% of the annual TN load to the estuary, but joins the estuary close to the sea. It is unlikely to have a strong influence on the upper part of the estuary above the Hina Hina Rd bridge.

The two-compartment model has tuning factors for the upper and lower parts of the estuary that are calculated from observed salinities (

Table **6-4**).

Table 6-4: Calibration of the two-compartment estuary mixing model for the Catlins Estuary.

Part of estuary	Tidal prism (m³)	Freshwater inflow (m³/s)	Mean salinity	Observed Tuning parameter b	Reference tuning parameter b_0
Upper estuary	5,917,000	0.669	31.3202	0.947	0.955
Lower estuary	5,045,000	0.345	34.2945	0.572	0.575

We use the two-compartment model to estimate the dilution and therefore potential nutrient concentration under mean flow conditions for the upper and lower parts of the Catlins Estuary (Table 6-5). The upper estuary has a higher fraction of fresh water than the lower estuary (28% versus 5%)

and, of that fresh water, approximately 1/20th originated from the Owaka River. Consequently, nutrient concentrations in the Owaka River have only a minor influence on the upper Catlins Estuary. The upper estuary also has a moderately long flushing time (5.1 days), while the lower estuary flushes quickly.

In the lower estuary, the relative fractions of fresh water originating from each river are in proportion to the river flows (i.e., the Catlins River contributes 61% of the total inflow to the estuary, and therefore 61% of the freshwater in the lower estuary originates from the Catlins River). As both rivers have similar mean flows, the relative influence of each river on the eutrophic condition of the lower estuary is related to their nutrient loads.

The upper Catlins estuary has a C banding, based on macroalgae susceptibility, while the lower estuary has a B banding (Table 6-5). The very high phytoplankton banding for the upper estuary indicates that high chlorophyll *a* concentrations or discolouration may be observed on occasions, but it is unlikely that this will trigger secondary symptoms of eutrophication because, as noted above, it is a SIDE.

Table 6-5: Results of dilution modelling using a two-compartment model for the Catlins River Estuary. The overall ETI susceptibility for each compartment is based on the macroalgae susceptibility due to the high intertidal areas and shallow mean depths.

Estuary	Mean river TN concentration (mg/m^3)	Ocean TN concentration (mg/m^3)	Estuary freshwater fraction	Estuary TN	Estuary flushing time (days)	Macroalgae susceptibility	Phytoplankton susceptibility	ETI Susceptibility
Upper Catlins	750	40	28%	260	5.1	C	D	**C**
Lower Catlins	1810	40	5%	99	0.46	B	A	**B**

7 Comparison of susceptibility metrics with observed estuarine state

7.1 Shag River Estuary

The ecological qualities (Table 6.1) expected from SIDE type estuaries, like Shag River Estuary, that have a high susceptibility to macroalgal eutrophication (Band C) are:

- Persistent, high macroalgal cover (25–50%) and/or biomass (>200 - 1000 g/m^2 wet weight), often with entrainment in sediment.
- Sediment quality degraded
- Ecological communities (e.g., bird, fish, seagrass, and macroinvertebrates) moderately to strongly impacted by macroalgae.

Recent broad-scale habitat mapping by (Stevens and Robertson 2017b) assessed opportunistic macroalgal growth by mapping the spatial spread and density of macroalgae in available intertidal habitat in the Shag River Estuary and calculating an "Ecological Quality Rating" (EQR) (Borja et al. 2007). The estuary supported <1% opportunistic macroalgal cover within the Available Intertidal Habitat (AIH), confined to two small areas near the entrance dominated by the green alga *Ulva intestinalis.* The resulting EQR was 0.9. The macroalgae quality status was given as 'high', and the risk rating 'low'. Previous sampling (Stewart 2007) also recorded low intertidal macroalgal cover (0.7 ha) in the estuary. However, (Robertson et al. 2017b) noted high concentrations of phytoplankton in areas of the water column in the upper estuary and dense beds of macroalgae in channels in the lower estuary, which Stevens and Robertson (2017b) suggested were evidence of nutrient driven increases in algal growth.

Sediment condition measured by Robertson et al. (2017b) showed a combination of moderate muddiness and poor sediment oxygenation that have resulted in an 'unbalanced to impoverished type macroinvertebrate community'.

From the Stevens and Robertson (2017b) broad scale report that included fine scale monitoring results, the Shag River Estuary had an overall ETI score of 0.35 and a risk indicator rating of 'Low' (ETI band B). Differences between field-measured trophic indicators (Stevens and Robertson 2017b) and the dilution model-derived susceptibility metrics in the current report highlight remarkably little macroalgal growth in the Shag River Estuary considering its current nutrient load. However, field-measured sediment conditions broadly agree with those for a dilution model susceptibility 'C' banding.

7.2 Catlins Estuary

Ecological qualities expected from SIDE type estuaries, like The Catlins, that have a high susceptibility to macroalgal eutrophication (Band C) are as for the Shag River Estuary, above. However, as shown in Table 6-5, a different banding (Band B) is more appropriate in the lower Catlins Estuary. The ecological qualities expected from SIDE type estuaries that have a moderate susceptibility to macroalgal eutrophication (Band B) are (Table 6-1):

- Limited macroalgal cover (5–20%) and low biomass (50–200 g/m^2 wet weight) of opportunistic macroalgal blooms and with no growth of algae in the underlying sediment.

- Sediment quality transitional.
- Ecological communities (e.g., bird, fish, seagrass, and macroinvertebrates) slightly impacted by additional macroalgal growth arising from nutrients levels that are elevated.

Predicted macroalgal cover appears higher in both the upper and lower estuaries than that observed in recent broad-scale habitat mapping by Stevens and Robertson (2017a). The EQR score calculated by Stevens and Robertson (2017a) for the estuary was 0.62 – a quality status of 'Good'. This reflected isolated pockets of macroalgal growth, with relatively low overall growth. Stevens and Robertson noted however that there were indications of excessive growth present with moderate biomass in some parts of the estuary, particularly the poorly flushed upper intertidal flats of Catlins Lake, and the lower tidal channels of the Owaka River where sediment entrained growths of the red alga *Gracilaria chilensis*. Stevens and Robertson (2017a) also noted that a previous study (Stewart, 2012) had reported only two moderate patches of the opportunistic macroalga *Ulva* from the Owaka arm in 2012, and Stewart and Bywater (2009) reported no growths of *Gracilaria* in Catlins Lake in 2008. We note that the suggestion by Stevens and Robertson (2017a) of a deterioration in macroalgal condition over past 4–8 years may result from increasing TN loads to Catlins Estuary (Figure 2-3 in this report).

Macroalgal EQR is one of the primary indicators of estuarine trophic condition used in the ETI tool 2 score (Zeldis et al. 2017b). Data from broad scale (Stevens and Robertson 2017a) and fine scale monitoring (Robertson et al. 2017a) were combined in Stevens and Robertson (2017a) to give an ETI score of 0.63 for the greater Catlins Estuary (upper and lower estuary areas combined) – indicating a risk rating of 'moderate' for eutrophic symptoms. This calculation incorporated sediment oxygenation, nitrogen and organic carbon content, and macroinvertebrate community data as well as the macroalgal cover data. Notably, results for sediment oxygenation and macroinvertebrate communities were distinctly more indicative of eutrophic, degraded conditions in the upper Catlins Lake section of the estuary. This section of the estuary showed a Macroinvertebrate Enrichment Index (NZ AMBI) (Robertson et al. 2015) rating of 'poor'. The more oligotrophic seaward estuary site had a NZ AMBI rating of 'normal', the best possible score. The overall 'moderate' ETI ranking based on observed estuarine state for the greater Catlins Estuary agrees with the modelled combined ASSETS physical and N-load susceptibility ranking of 'moderate' (Table 5-1), and the combined ETI susceptibility C banding (Table 6-3).

8 Catchment load bandings

To aid management decisions, we present the catchment loadings from the estuaries' respective terminal 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. 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 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.

8.1 Shag River Estuary

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

Table 8-1: Annual freshwater TN loads to the Shag River Estuary required to meet each ETI tool 1 band of eutrophication susceptibility from macroalgal growth. Based on the Plew et al. (in prep.) CLUES-Estuary tool.

Macro-algal banding			
Band A (T/yr)	Band B (T/yr)	Band C (T/yr)	Band D (T/yr)
<14	14 – 54	54 – 205	>205

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 2.494 m^3/s (the mean flow estimate: Table 2-1).

8.2 Catlins Estuary

Load bandings for the Catlins Estuary are more difficult to define because there are two inflows that affect the estuary. Figure 8-1 illustrates the bandings for the upper and lower estuary that result from various combinations of annual TN loads from the two rivers. The upper estuary is more sensitive to loads from the Catlins River (a smaller increase in load is required to change bands) than the Owaka River. The lower estuary is nearly equally sensitive to loadings from both catchments.

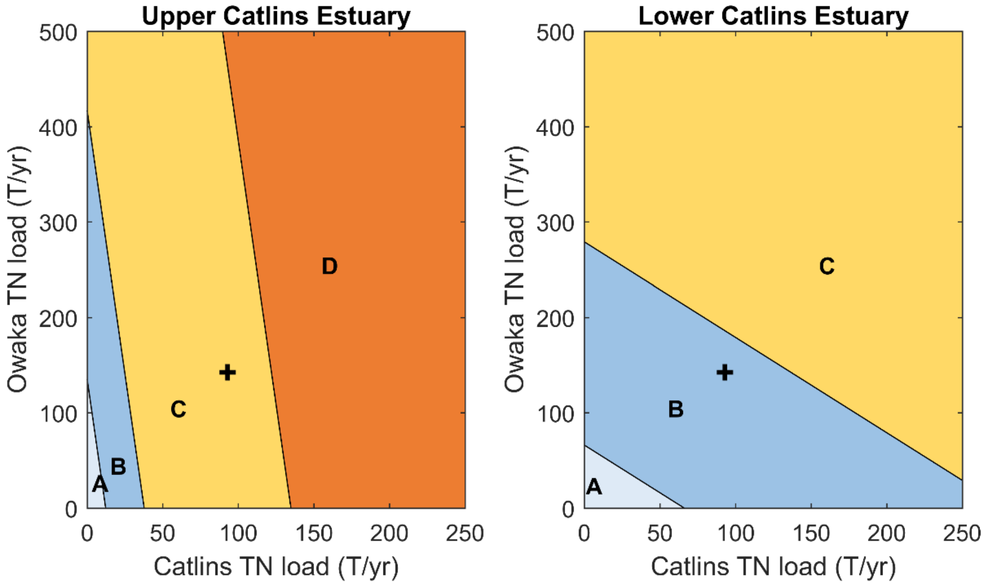

Figure 8-1: Macroalgae susceptibility bandings of the upper and lower Catlins River Estuary for catchment loads from Catlins River and Owaka River. Mean flow conditions assumed for each river. The + indicates present day mean annual loads.

The upper estuary is generally more susceptible than the lower estuary. However, the lower estuary can be more susceptible to macroalgae than the upper estuary when N loadings from the Catlins River are small. For example, in the situation where TN load from the Catlins River is zero, and TN load from the Owaka River is 300 T/yr, we would expect higher macroalgal growth in the lower estuary. Combined susceptibility been assessed by taking the worst macroalgae banding from the upper or lower estuary (Figure 8-2).

Present day loads are indicated by the + symbols in Figure 8-2. We can infer from this figure that a relatively small (~20 T/yr) increase in load from the Catlins River will increase the susceptibility of the Catlins Estuary banding to D (very high), while an increase of over 300 T/yr from the Owaka River is required to cause a similar impact. Conversely, a reduction in load of ~60 T/yr from the Catlins River would be required to achieve a B susceptibility band. It would not be possible to obtain a B banding by only reducing loads from the Owaka River.

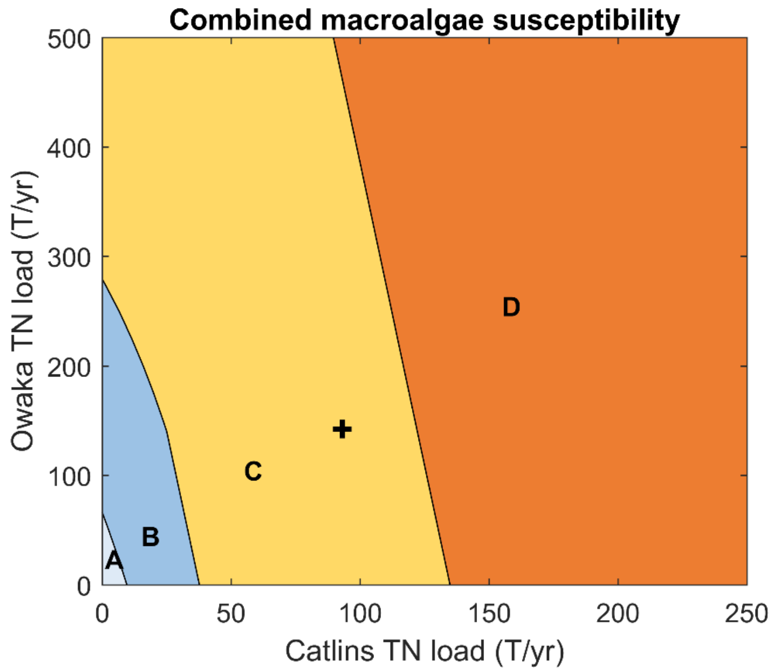

Figure 8-2: Macroalgae susceptibility of the Catlins River Estuary to total nitrogen loads from the Catlins River and Owaka River. This figure shows the highest susceptibility band in either upper or lower estuary for catchment load combinations. The + symbol indicates present mean annual TN loads.

For illustrative purposes, Table 8-2 shows annual TN loadings from the Catlins River required to achieve ETI macroalgae susceptibility bandings of A, B, C or D for different Owaka River loads. The Owaka River loads have been set at 25%, 50%, 100%, and 150% of present day (2013–17 average) mean annual TN loads. Note that an A band cannot be obtained with Owaka River loads > 67 T/yr TN.

Table 8-2: Annual freshwater TN loads from the Catlins River required to meet each ETI tool 1 band of eutrophication susceptibility from macroalgal growth. Load bandings are shown for Owaka River TN loads set at 25%, 50%, 100% and 150% of present day levels.

Owaka River load	Macro-algal banding			
(T/y)	Band A (T/yr)	Band B (T/yr)	Band C (T/yr)	Band D (T/yr)
35	<9	9-35	35 – 132	>132
71	-	0 – 31	31 – 128	>128
142	-	0 – 25	25 – 123	>123
213	-	0 – 18	18 – 116	>116

9 References

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* 55:42-52.

Dudley, B. D., Zeldis, J., Burge, O. (2017) New Zealand Coastal Water Quality Assessment. National Institute of Water and Atmospheric Research, Christchurch, New Zealand.

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* 51:364-376.

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* 50:389-417.

Plew, D. R., Zeldis, J.R., Shankar, U., Elliot, A.H. (2018) Using simple dilution models to predict New Zealand estuarine water quality. Estuaries and Coasts in press.

Robertson, B., 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. . Estuarine Trophic Index, MBIE/NIWA Contract No: C01X1420.

Robertson, B. M., Robertson, B.P., Stevens, L.M. (2017a) Catlins Estuary: Fine Scale Monitoring 2016/17. Report prepared by Wriggle Coastal Management for Otago Regional Council. 32p.

Robertson, B. M., Robertson, B.P., Stevens, L.M. (2017b) Shag Estuary: Fine Scale Monitoring 2016/17. Report prepared by Wriggle Coastal Management for Otago Regional Council. 31p.

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 adn Assessing Estuary Trophic State. MBIE/NIWA Contract No: COX1420.

Robertson, B. P., Gardner, J.P.A., Savage, C. (2015) Macrobenthic–mud relations strengthen the foundation for benthic index development: A case study from shallow, temperate New Zealand estuaries. *Ecological indicators* 58:161-174.

Stevens, L. M., Robertson, B.M. (2017a) Catlins Estuary: Broad Scale Habitat Mapping 2016/17. Report prepared by Wriggle Coastal Management for Otago Regional Council. 38p.

Stevens, L. M., Robertson, B.M. (2017b) Shag Estuary: Broad Scale Habitat Mapping 2016/17. Report prepared by Wriggle Coastal Management for Otago Regional Council. 26p.

Zeldis, J. R., Whitehead, A.L., Plew, D., Madarasz-Smith, A., Oliver, M., Stevens, L.M., Robertson, B., Storey, R., Burge, O., Dudley, B. (2017a) The New Zealand Estuary Trophic Index (ETI) Tools: Web Tool 1 - Determining Eutrophication Susceptibility using Physical and Nutrient Load Data. Ministry of Business, Innovation and Employment Envirolink Tools Contract: C01X1420.

Zeldis, J. R., Whitehead, A.L., Plew, D., Madarasz-Smith, A., Oliver, M., Stevens, L.M., Robertson, B., Storey, R., Burge, O., Dudley, B. (2017b) The New Zealand Estuary Trophic Index (ETI) Tools: Web Tool 2 - Assessing Estuary Trophic State using Measured Trophic Indicators.

Appendix A CLUES-estuary dilution model

Two forms of dilution model are used in this report. Both are modified tidal-prism models. A single compartment model is sufficient for the Shag River Estuary. A two compartment model was developed for the Catlins River Estuary to account for the two distinct parts of the estuary (upper and lower) and the two inflows (Catlins River and Owaka River).

Single compartment tidal prism model

The single compartment model is described in Plew et al. (2018), but summarised briefly here.

The tidal flow in and out of the estuary is averaged over the tidal period T, and the concentration of a tracer in the estuary is solved for the estuary at high tide. The mass balance for the tracer is illustrated in Figure A-1.

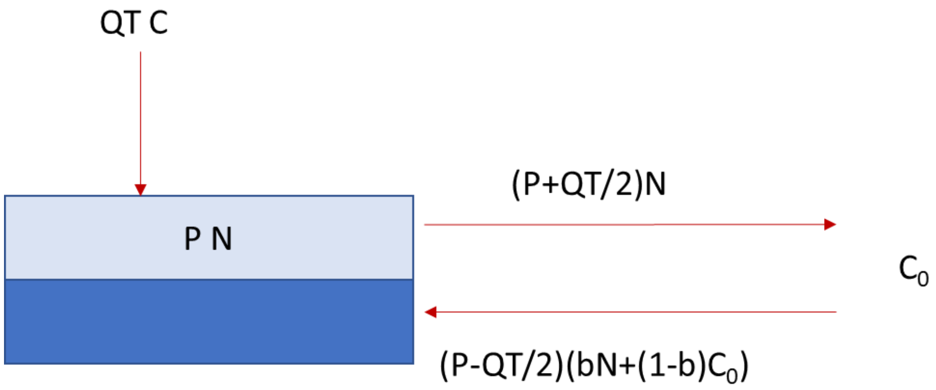

Figure A-1: Mass balance for a tracer in an estuary with a single compartment.

The terms in Figure A-1 are as follows:

Q = freshwater inflow (m^3/s)

T = tidal period (12.42 x 3600 s)

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

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

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

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

b = tuning factor (-)

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

The solution for b is

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

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

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

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

$$N = \frac{C}{D} + C_0\left(1 - \frac{1}{D}\right)$$

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

$$T_F = \frac{V}{QD}$$

Where V is the estuary volume at high tide.

Two compartment tidal prism model

Because the Catlins River Estuary consists of two distinct parts, with the upper estuary receiving inflow from the Catlins River, and the lower estuary also receiving inflow from the Owaka River, a two compartment tidal prism model has been created following a similar methodology. The mass balance for a tracer is illustrated in Figure A-2.

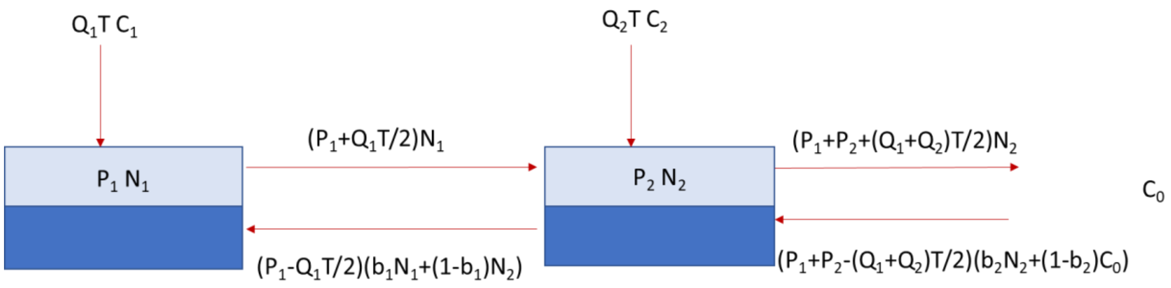

Figure A-2: Mass balance for a tracer in an estuary with two compartments and two inflows.

The terms in Figure A-2 are as follows:

Q_1 = freshwater inflow from river 1, into compartment 1 (m^3/s)

Q_2 = freshwater inflow from river 2, into compartment 2 (m^3/s)

P_1 = tidal prism in compartment 1 (m^3)

P_2 = tidal prism in compartment 2 (m^3)

N_1 = concentration of the tracer in compartment 1 (mg/m^3)

N_2 = concentration of the tracer in compartment 1 (mg/m^3)

C_1 = concentration of the tracer in freshwater inflow 1 (mg/m^3)

C = concentration of the tracer in freshwater inflow 2 (mg/m^3)

b_1 = tuning factor for compartment 1 (-)

b_2 = tuning factor for compartment 2 (-)

The tuning factors are determined from measured volume-averaged salinities (at high tide) in each compartment

$$\boldsymbol{b_1 = \frac{P_1 - q_1\left(\frac{S_2}{S_2 - S_1} - \frac{1}{2}\right)}{P_1 - \frac{q_1}{2}}}$$

$$\boldsymbol{b_2 = 1 - \frac{q_1 S_1 + q S_2}{\left(P - \frac{q}{2}\right)(S_0 - S_2)}}$$

Where:

S_1 = salinity in compartment 1

S_2 = salinity in compartment 2

$q_1 = Q_1T$

$q = (Q_1+Q_2)T$

$P = P_1+P_2$

The concentration of a tracer in each compartment can then be calculated using the tuning factors. First, the concentration in the lower compartment (N_2) is calculated:

$$\boldsymbol{N_2 = \frac{q_1 C_1 + q_2 C_2 + \left(P - \frac{q}{2}\right)(1 - b_2)N_0}{\left(P - \frac{q}{2}\right)(1 - b_2) + q}}$$

Then the concentration in the upper compartment (N_1) can be determined.

$$\boldsymbol{N_1 = \frac{\left(P_1 - \frac{q_1}{2}\right)(1 - b_1)N_2 + q_1 C_1}{\left(P_1 - \frac{q_1}{2}\right)(1 - b_1) + q_1}}$$