Canterbury region estuary eutrophication susceptibility assessment

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Executive summary

Environment Canterbury Regional Council (CRC) commissioned NIWA to calculate the eutrophication susceptibility of the Avon-Heathcote Estuary, Okains Bay Estuary and Le Bons Bay Estuary according to the recently released Envirolink Tools screening tool 1 for the New Zealand Estuary Trophic Index (Robertson et al. 2016) (ETI tool 1).

For the Avon-Heathcote Estuary, a catchment strongly influenced by urban environments, we used N loads and river flow data previously established by Burge (2007) in our assessment. Flow and nutrient load data for the Okains Bay and Le Bons Bay estuaries were derived from NIWA's NZRiverMaps web tool. We compared these predictions with those made by the Catchment Land Use and Environmental Sustainability (CLUES) GIS model, and to flow recorder data from ECAN's Opara Stream site in Okains Bay.

Under current flow conditions, the ASSETS approach used in ETI tool 1 the Avon-Heathcote Estuary sits within a high physical susceptibility banding , while Okains Bay Estuary and Le Bons Bay Estuary sit within the moderate physical susceptibility banding.

Because the dilution potential for Le Bons Bay and Okains Bay estuaries are substantially below those for which the ASSETS approach is designed, this approach is not appropriate for estimating their physical susceptibility. Hence, we also used the CLUES-Estuary-derived calculation of eutrophication susceptibility for these estuaries.

Estuary N loads per unit area were calculated from terminal reach nutrient loads and estuary surface areas. The Avon-Heathcote and Le Bons Bay estuaries have loadings between 50-250 $mg/m^2/d$, which indicate a high N-load susceptibility, according to the ASSETS approach. Okains Bay Estuary has a loading of between 10-50 $mg/m^2/d$ indicating a moderate N-load susceptibility.

The Avon-Heathcote Estuary showed a high combined physical and nutrient load susceptibility (Band C) using the ASSETS approach. Using the CLUES-Estuary estimate of eutrophication susceptibility gave a result for the Avon-Heathcote Estuary of moderate susceptibility to macroalgal eutrophication (Band C), and high susceptibility to phytoplankton eutrophication (Band D). Under loading conditions prior to the 2010 diversion of the wastewater discharge, the Avon-Heathcote Estuary scored in Band D (very high) for combined ASSETS physical and N-load susceptibility, and in Band D (high) for both macroalgae and phytoplankton using the CLUES-estuary approach. The subsequent, post-diversion shift to Band C for combined ASSETS physical and N-load susceptibility, and Band C for macroalgae using the CLUES-Estuary approach is supported by recent studies showing reductions in macroagal growth and sediment recovery within the estuary.

Okains Bay Estuary showed a moderate combined physical and nutrient load susceptibility (Band B) using the ASSETS approach. Using the CLUES-Estuary estimate of eutrophication susceptibility, Okains Bay Estuary showed moderate susceptibility to macroalgal eutrophication (Band B), and low susceptibility to phytoplankton eutrophication (Band A).

Le Bons Bay Estuary showed a high combined physical and nutrient load susceptibility (Band C) using the ASSETS approach. Using the CLUES-Estuary estimate of eutrophication susceptibility, Le Bons Bay Estuary showed moderate susceptibility to macroalgal eutrophication (Band B), and low susceptibility to phytoplankton eutrophication (Band A).

The ratings indicating low susceptibility macroalgal growth for both Okains Bay and Le Bons Bay (Clues-Estuary 'B' macroalgal bands) are consistent with the absence of extensive macro algae growth in the estuaries at the time of the bathymetric field surveys.

We conclude that the ETI tools employed give a good indication of ecological condition in the three estuaries surveyed. However, we note that ETI tool 1 is intended only to enable the prioritisation of estuaries for more rigorous monitoring and management, and baseline ecological monitoring may be appropriate for Le Bons Bay Estuary and Okains Bay Estuary, particularly if changes to catchment N loading or freshwater flows are anticipated.

1 Introduction

To gain an understanding of how current freshwater and nutrient flows may affect the ecological health of estuaries in the Canterbury region, Environment Canterbury Regional Council (CRC) requested that NIWA determines the eutrophication susceptibility of the Estuary of the Heathcote and Avon Rivers/Ihutai (Avon-Heathcote Estuary), Okain's Bay Estuary and Le Bons Bay Estuary using Envirolink Tools screening tool 1 for the New Zealand Estuary Trophic Index (Robertson et al. 2016) (ETI tool 1) based on current land use in the tributary catchments for these estuaries. This work entailed:

- Determination of estuary type for each estuary according to ETI tool 1.
- A field survey to obtain the estuary volume and tidal prism for Le Bons Bay and Okains Bay estuaries.
- Determination of the flushing and dilution potential of each estuary according to ETI tool 1 using freshwater inflow data, and estuary volume and tidal height data available to NIWA.
- Calculation of the physical susceptibility of for each estuary according to ETI tool 1.
- Calculation of estuary areal total dissolved N loads for each estuary as well as an estimate of current N-loading to 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 each estuary according to ETI tool 1.
- Because the Assessment of Estuarine Trophic Status (ASSETS) approach employed in ETI tool 1 is not appropriate for estimating the susceptibility for small estuaries (such as Le Bons Bay and Okains Bay estuaries: Robertson et al. 2016: 30), we used the CLUES-Estuary tool (Plew, Zeldis et al. in review) to predict potential nutrient concentrations and assess eutrophication susceptibility.
- A brief description of each estuary's ecological condition that corresponded to the combined physical and nutrient load susceptibility each estuary, and comparison of this information with recent ecological monitoring data.

The main sources of freshwater flow and nutrients for the Avon-Heathcote Estuary are the Avon and Heathcote rivers, and drains that run from Christchurch City to the estuary (Burge 2007). Freshwater flows to Okains Bay and Le Bons Bay estuaries are dominated by single rivers (Opara Stream and Le Bons Stream, respectively). The nutrient loads these rivers carry are heavily dependent on land use within catchments (Larned, Snelder 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), and the majority of N taken up by algae is in dissolved inorganic form. However, because N transported to estuaries in particulate form can be mineralised to inorganic forms within estuaries, total N supplies from inflows, and nutrient retention within estuaries are used to gauge estuarine eutrophication susceptibility.

Freshwater inflows influence the susceptibility of estuaries to eutrophication, because rivers supply the majority of nitrogen to estuaries. Eutrophic conditions in estuaries can be driven by excessive growth of either benthic macro-algae or suspended phytoplankton. Macro-algae growth is driven largely by water column nutrient concentrations, while phytoplankton growth also depends on the flushing time (or residence time) of an estuary. Longer residence times tend to produce more eutrophic conditions because algae in the water column (phytoplankton) have time to grow and multiply within the estuary. Here, we consider these factors to assess the susceptibility of Avon-Heathcote, Okains Bay and Le Bons Bay estuaries to macroalgal and phytoplankton eutrophication based on current N-loading, flow and flushing information.

2 Flow and N-load calculations

For the Avon-Heathcote Estuary, we used N loads previously established by Burge (2007) of 170,000 kg/yr TN. The combined mean annual freshwater inflow from the Avon and Heathcote rivers is 2.47 m^3/s.

Flow and nutrient load data for the Okains Bay and Le Bons Bay estuaries were derived from NIWA's NZRiverMaps web tool https://shiny.niwa.co.nz/nzrivermaps/. This tool collates statistical and empirical predictions of a number of properties for river reaches across New Zealand (Unwin and Larned 2013; Booker and Woods 2014). We compared these predictions with those made by the CLUES GIS model, and to flow recorder data from ECAN's Opara Stream site in Okains Bay.

NZRiverMaps gives mean annual inflows into the Okains Bay Estuary of 0.324 m^3/s. CLUES gives a higher estimate of 0.717 m^3/s. We use the NZRiverMaps estimates because a comparison between predicted mean flow in a river reach on the Opara Stream shows excellent agreement with mean flow from a flow recorder maintained by ECAN (NZRiverMaps 0.260 m^3/s, measured 0.267 m^3/s). This site is on the lower reach of the Opara Stream, but the estuary also receives inflow from minor tributaries below this point.

Okains Bay Estuary N-loads were estimated from the mean annual inflow (0.324 m^3/s) and median total nitrogen concentrations (595 µg/l) predicted by NZRiverMaps. We assume, for the purpose of this report, that median and mean TN concentrations are similar and that all N is potentially available for uptake by algae. The annual load is 6080 kg/yr. CLUES gives a much higher N-load estimate (23 980 kg/yr), which results from higher predictions of inflow (0.717 m^3/s) and gives higher mean concentration (1061 µg/l). Some of the discrepancy may also result from the use of median concentrations from NZRiverMaps, which may be lower than mean concentrations if TN concentrations are higher during high flows. The CLUES predicted TN concentrations appear high for this catchment, but we have no data to confirm either prediction.

Le Bons Bay Estuary N-loads were also calculated from NZRiverMaps' mean annual flow (0.381 m^3/s) and median nitrogen concentration (464 µg/l). The mean annual N-load of 5580 kg/yr is smaller than the 13 320 kg/y estimated from CLUES. CLUES also gives higher estimates for both inflow volume (0.628 m^3/s) and concentration (672 µg/l). However, we use the NZRiverMaps estimates, rather than CLUES, as it appears CLUES over-estimates flow and, possibly, concentration, in the neighbouring Okains Bay catchment.

Table 2-1: Mean annual flow and annual nutrient loads into the Avon Heathcote, Okains Bay and Le Bons Bay estuaries. Avon Heathcote values from Burge (2007), and Okains and Le Bons Bay values from NZRiverMaps.

Estuary	Mean flow (m^3/s)	TN load (kg/yr)
Avon Heathcote	2.47	170,000
Okains Bay	0.324	6,080
Le Bons Bay	0.381	5,580

3 Bathymetric surveys

Volumes and surface areas for the Avon-Heathcote Estuary were extracted from a digital elevation model created from the 2013 post-earth quake survey (Measures and Bind 2013). Tidal prisms at spring and mean tides were calculated from differences in volume within the estuary at high and low tides.

Bathymetry data for Le Bons Bay Estuary (Figure 3-1) were obtained by combining measurements from a kayak-mounted echo sounder taken over wetted parts of the estuary at high tide (22 March 2017), with drone-acquired photogrammetry for the upper part of the estuary obtained at low tide (22 March 2017), and laser scan data for the lower part of the estuary obtained low tide (11 May 2017). Data points were ground-truthed using RTK-GPS measurements. The tidal range at the coast during the time of the survey was -0.60 m to + 0.56 m. However, water levels inside the estuary did not drop below 0 m at low tide, and the highest water level observed inside the estuary at high tide was 0.45 m. The mouth acts as both a sill preventing the estuary draining fully at low tide, and as a constriction to inflows, such that water levels inside the estuary at high tide were 20 per cent lower than at the coast.

Bathymetry data for Okains Bay Estuary (Figure 3-2) were obtained in a similar manner, using echo-sound data for submerged parts of the estuary obtained at high tide (23 March 2017), and laser scan data for the intertidal areas obtained on 31 March 2017. The tidal range inside the estuary varied between -0.60 m and +0.55 m, which is very close to the predicted tidal range at the coast (from NIWA Tide forecaster) of -0.63 m to +0.59 m. Thus, the estuary mouth appears to present a small constriction only, reducing the estuary's tidal range by only ~5-7 per cent compared to at the coast.

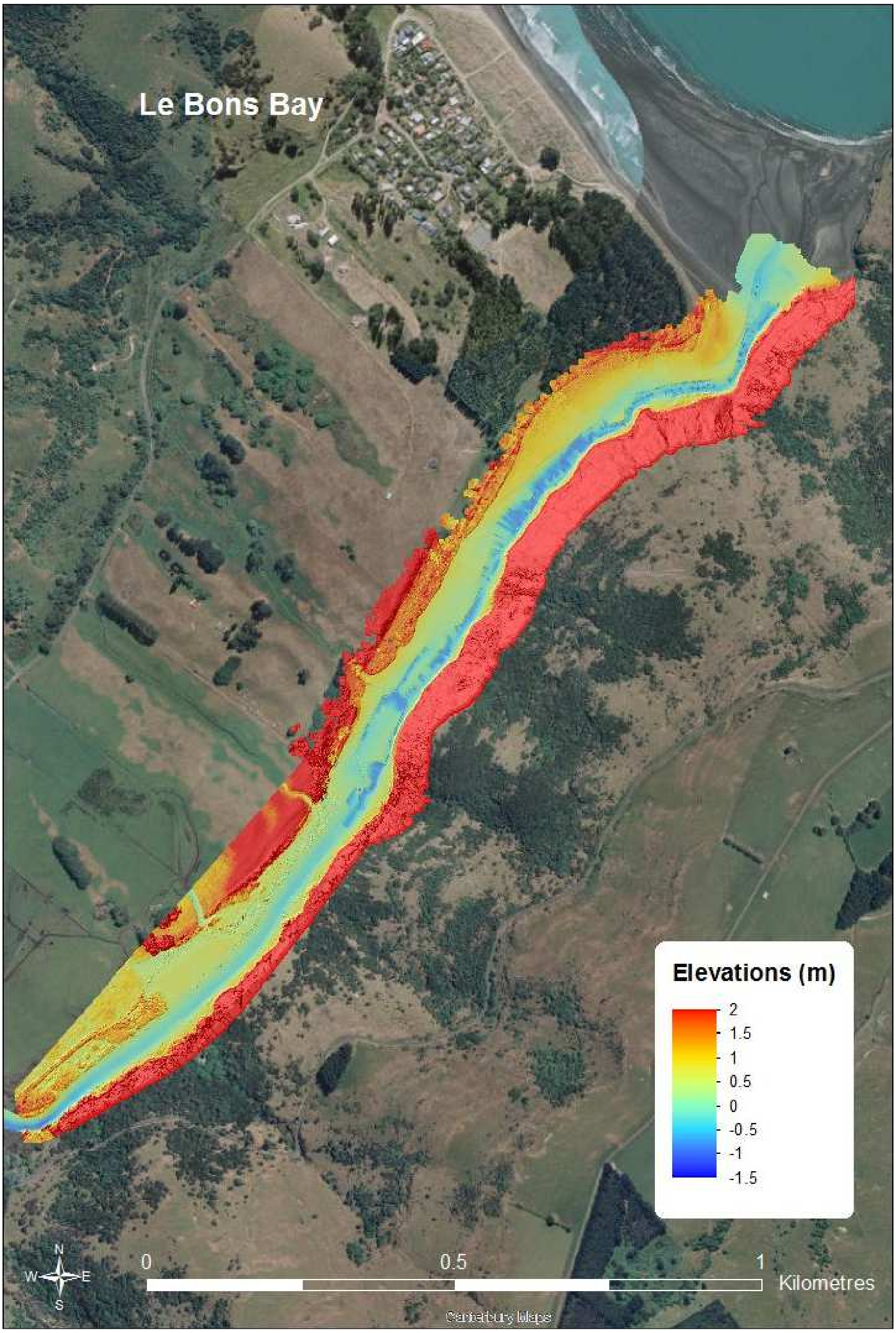

Figure 3-1: Elevation map of Le Bons Bay Estuary obtained by combining measurements from a kayak-mounted echo sounder, photogrammetry for the upper part of the estuary and laser scan data for the lower part of the estuary. Cooler colours indicate lower elevation.

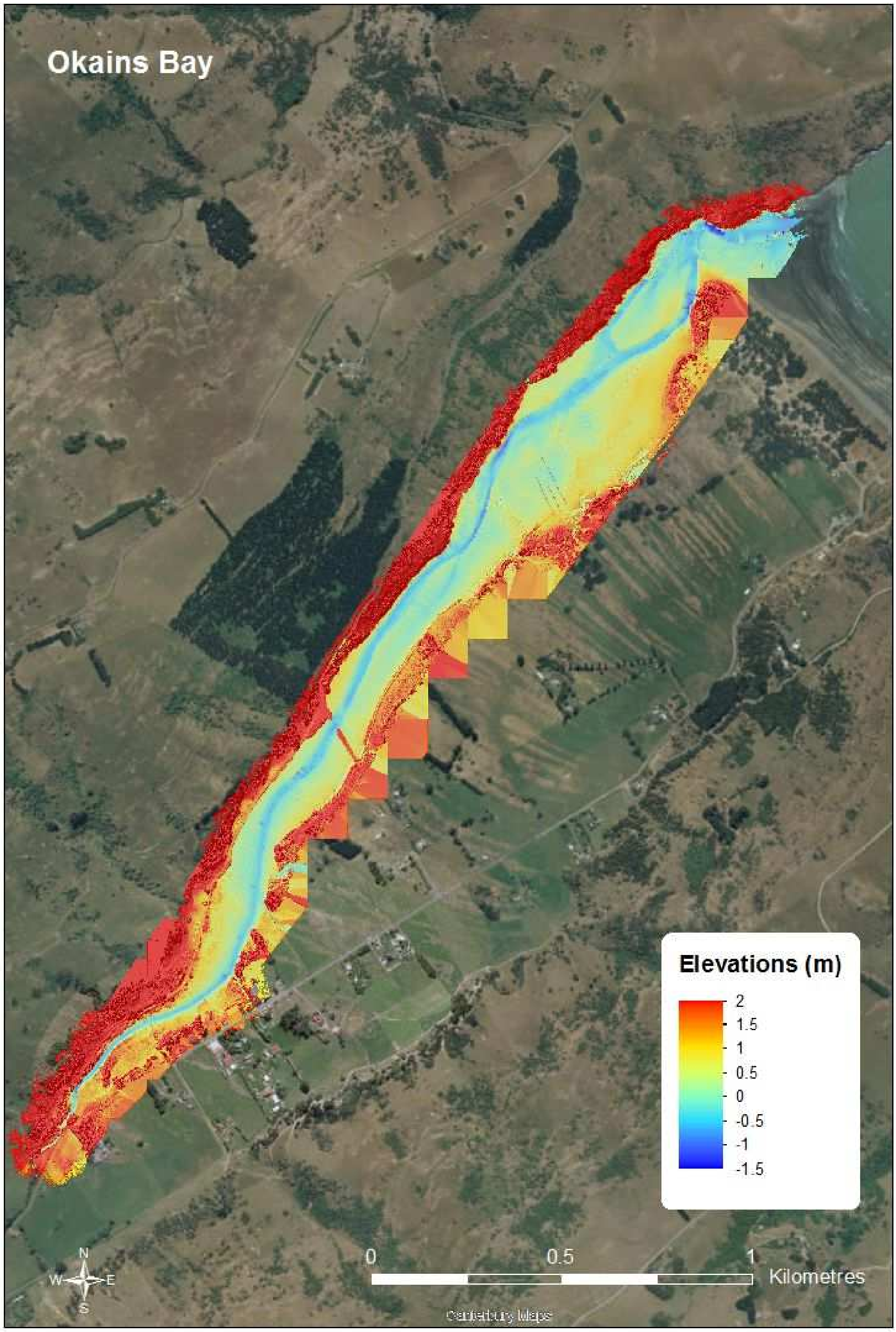

Figure 3-2: Elevation map of Okains Bay Estuary obtained by combining measurements from using echo-sound data for submerged parts of the estuary, and laser scan data for the intertidal areas. Cooler colours indicate lower elevation.

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 each of the three estuaries by physiographical type according to ETI tool 1. The spring tide tidal ranges for all three estuaries were obtained from NIWA's Coastal Explorer Database. Mean depth, surface area and percent intertidal area at mean high water springs (MHWS) were derived from the bathymetric data (Table 4-1).

Water levels in Okains Bay Estuary agreed well with tide levels forecast for the coast, with only a 5 per cent reduction in tidal range. Volume, surface area and intertidal area was calculated from the mapped bathymetry, assuming that the tidal range at spring tide inside the estuary was 5 per cent smaller than at the coast.

At Le Bons Bay, observations during the field survey suggest that the entrance channel constricts incoming tidal flow. This results in a lower water level (20% less) inside the estuary than at the coast at high tide. At low tide, the water levels in the estuary did not drop below 0.0 m elevation, which may be due to a sill or bar near the estuary mouth. Surface area was calculated from volume at MHWS, assuming that water levels were 20 per cent lower than at the coast, and mean depth was calculated from volume at MHWS (less 20%) divided by surface area. Intertidal area was calculated from the difference in area at MHWS (less 20%) and area at 0 m water level, which was the lowest level recorded inside the estuary during our survey.

Table 4-1: Mean depth, total surface area tidal range and intertidal area data for Avon-Heathcote, Okains Bay and Le Bons Bay estuaries. Mean depth, surface area and tidal range are calculated at Mean High Water Springs (MHWS).

Estuary	Mean depth (m)	Surface Area (km^2)	Intertidal Area (%)	Tidal Range at coast (m)
Avon-Heathcote	1.248	7.7236	61	1.79
Okain's Bay	0.677	0.4221	99	1.78
Le Bons Bay	0.566	0.1320	66	1.77

Based on these data, all three estuaries are classified as Shallow Intertidal-dominated Estuaries (SIDE), defined in ETI tool 1 as <3 m depth, residence time <3 days 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 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. Applying this to the Avon-Heathcote Estuary with a moderate tidal range (as defined in ASSETS), total mean annual flow into the estuary in the range of 2.13 x 10^5 m^3/day, and an estuary volume of 9,634,000 m^3, gives a flushing potential of 0.02 (Table 5-1). Comparison with the ETI bandings of flushing potentials (high: 10^0 – 10^{-1}; moderate: 10^{-2}, and low: 10^{-3} – 10^{-4}) shows that the Avon-Heathcote Estuary flushing potential is moderate.

Okains Bay has a moderate tidal range. The annual mean daily inflow is estimated as 28,000 m^3/day using NIWA's NZ River Maps statistical model (https://shiny.niwa.co.nz/nzrivermaps/). The estuary volume at MHWS is 285 900 m^3, giving a flushing potential of 0.1 which is in the high band.

Le Bons Bay also has a moderate tidal range, with an estimated annual mean daily inflow of 32,900 m^3/day. The estuary volume, calculated at MHWS and assuming that water levels in the estuary were 20 per cent less than at the coast, is 74,800 m^3 results in a flushing potential of 0.4 which is in the high band.

Table 5-1: Calculated flushing potentials for three Canterbury estuaries. Based on Robertson et al.'s (2016) Estuarine Trophic Index Tool 1. Data for all flow scenarios were derived from NIWA's NZ River Maps statistical model (https://shiny.niwa.co.nz/nzrivermaps/).

Estuary	Mean annual freshwater input (m^3/day)	Estuary volume at spring high tide (m^3)	Flushing potential	Flushing potential band (ETI tool 1)
Avon-Heathcote	2.13 x 10^5	9,634,000	0.02	Moderate
Okains Bay	2.80 x 10^4	285,900	0.1	High
Le Bons Bay	3.29 x 10^4	74,800	0.4	High

6 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. The Avon-Heathcote's dilution potential value is 2.9×10^{-9}. This places this estuary in the low band (10^{-10}-10^{-9}) for dilution potential. Dilution potentials for Okains Bay and Le Bons Bay are 9.9×10^{-8} and 3.8×10^{-7}, respectively, less than 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 Okains Bay and Le Bons Bay. Thus, in the absence of defined dilution potential bandings for small estuaries, we define all three estuaries as having low dilution potentials.

7 Physical susceptibility

Under current flow conditions, the moderate flushing potential and low dilution potential scores identify the Avon-Heathcote Estuary as **highly physically susceptible,** using the ASSETS categories (Table 6-1).

Okains Bay Estuary has a high flushing potential and low dilution potential, identifying the estuary as **moderately physical susceptible**.

Le Bons Bay Estuary has a high flushing potential and low dilution potential, identifying the estuary as **moderately physical susceptible**.

Table 7-1: ASSETS physical susceptibility classification system for shallow intertidal-dominated estuaries. Table from ETI Tool 1 (Robertson, Stevens et al. 2016).

		Dilution potential		
Flushing potential		High	Moderate	Low
	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 Okains Bay and Le Bons Bay estuaries because their dilution potentials are substantially less than those for estuaries used to develop the ASSETS approach. Hence, we recommend considering the CLUES-Estuary-derived calculation of eutrophication susceptibility for these estuaries (see section 9 below).

8 Nitrogen loads and nutrient load susceptibility

Estuary N loads per unit area were calculated from terminal reach nutrient loads. For the Avon-Heathcote, the contributing water bodies were the Avon and Heathcote rivers, and six drains flowing from the city to the estuary (Burge 2007). N loads for Okains Bay and Le Bons Bay were estimated from NIWA's NZRiverMaps (see section 2) and CLUES model. These data and the N loads per unit area within the estuaries are presented in Table 8-1.

Avon-Heathcote and Le Bons Bay estuaries had loadings between 50-250 mg/m^2/d, which indicate high N-load susceptibilities, according to the ASSETS approach. Okains Bay had a loading of 39 mg/m^2/d, which indicates a moderate N-load susceptibility.

Table 8-1: Areal N-load susceptibility for three Canterbury estuaries under current N loads. Based on Robertson et al.'s (2016) Estuarine Trophic Index Tool 1. Data for Okains Bay Estuary and Le Bons Bay Estuary were derived from NIWA's Clues model (Elliot et al. 2016).

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)
Avon-Heathcote Estuary	170,000	7.724	60	High (50-250 mg/m^2/day)
Okains Bay	6,080	0.4221	39	Moderate (10-50 mg/m^2/day)
Le Bons Bay	5,580	0.1320	116	High (50-250 mg/m^2/day)

9 Combined physical and nutrient load susceptibility

Under the present flow and nutrient loading conditions, we assessed the Avon-Heathcote Estuary as having a high 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 9-1).

Okains Bay Estuary was assessed as having a moderate N load susceptibility and a moderate physical susceptibility. According to the ASSETS approach, this combinations results in a **moderate combined physical and nutrient load susceptibility** (Band B).

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

Table 9-1: Combined physical and nutrient load susceptibility bandings for shallow intertidal-dominated estuaries. Table from ETI Tool 1 (Robertson, Stevens et al. 2016).

		N load susceptibility (mg/m2/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

10 CLUES-Estuary estimate of eutrophication susceptibility

Because the ASSETS approach employed in the ETI tool does not define dilution potential for small estuaries, such as Okains Bay and Le Bons Bay with volumes <2.8 million m^3 (Robertson et al. 2016, page 30), we estimated potential nutrient concentrations for all three estuaries using the CLUES-Estuary approach (Plew, Zeldis et al. in review), as an alternative way to assess eutrophication susceptibility. The CLUES approach scores susceptibility to excessive phytoplankton growth and to excessive macroalgal growth separately, as two predictors of ecological impact, as described in (Table 10-1).

Table 10-1: Description of ecological quality for macroalgal and phytoplankton bandings Adapted from ETI tool 2 (Robertson, Stevens et al. 2016).

Band	A	B	C	D
Opportunistic Macroalgae	$N_{est} < 56$ mg/m^3 Ecological communities (e.g., bird, fish, seagrass, and macroinvertebrates) are healthy and resilient. Algal cover <5% and low biomass (<50 g/m^2 wet weight) of opportunistic macroalgal blooms and with no growth of algae in the underlying sediment. Sediment quality high.	$56 \le N_{est} < 180$ 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 (50-200 g/m^2 wet weight) of opportunistic macroalgal blooms and with no growth of algae in the underlying sediment. Sediment quality transitional.	$180 \le N_{est} < 350$ 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- 1000 g/m^2 wet weight), often with entrainment in sediment. Sediment quality degraded.	$N_{est} \ge 350$ 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 (>1000 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.

The CLUES-Estuary 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 absence of denitrification or uptake) in the estuary averaged over time and space. The potential nutrient concentration in the estuary N_{Est} is calculated as:

$$N_{Est} = \frac{N_R + N_O(D-1)}{D} \qquad (1)$$

The nitrogen concentration in the river inflows N_R is calculated by dividing the total annual nitrogen load by the total mean inflow from all of the river sources. The ocean nitrogen concentration N_O is obtained from the CARS (CSIRO Atlas of Regional Seas) climatology (CSIRO 2011). This value, 34.7 mg/m^3, is close to the mean recorded dissolved inorganic N concentration at sites at 3 km from the Canterbury coast over the duration of CRC records for these sites (55 mg/m^3, (Dudley, Zeldis et al. 2017)). The dilution factor D is the of freshwater within the estuary, with D = 10 indicating that the estuary water comprises 10% freshwater by volume and 90% seawater. For the estuaries in this study, a modified tidal prism model (Luketina 1998) was used to calculate the dilution factor. The dilution factor is calculated from the tidal prism P, freshwater inflow Q_F, tidal period T= 44712 seconds, and a tuning parameter b:

$$D = \frac{P(1-b) + \frac{Q_F T}{2}(1+b)}{Q_F T} \qquad (2)$$

The tuning parameter b accounts for return flow back into the estuary and incomplete mixing within the estuary. In the absence of empirical data, this parameter can be determined from the ratio of freshwater inflow to tidal prism (Plew, Zeldis et al. in review). Alternatively, this factor can be estimated from estuary-averaged salinity at high tide:

$$b = \frac{Q_F T\left(\frac{S_O}{S_O - S} - \frac{1}{2}\right) - P}{\frac{Q_F T}{2} - P} \qquad (3)$$

S is the volume averaged salinity of water in the estuary at high tide, and S_O the ocean salinity.

The flushing time scale, T_F, which represents the time (in days) required for river water entering the estuary to be flushed from the estuary is calculated as

$$T_F = \frac{V}{DQ_F} \qquad (4)$$

Predictions of phytoplankton are made using a simple growth model, and phytoplankton concentrations in the form of Chl-a concentrations are predicted from the potential nitrogen concentration and flushing time. The model assumes that phytoplankton growth is nitrogen limited, with a half saturation coefficient of 35 mg DIN/m^3, and a net specific growth rate of 0.43 day^{-1} (Eppley, Rogers et al. 1969). The predicted bandings are displayed as contours in Figure 10-1. The model predicts that phytoplankton will not grow if the flushing time of the estuary is brief (phytoplankton are flushed from the estuary faster than they can grow). If the flushing time is sufficiently long, then phytoplankton concentrations increase as the potential nutrient concentrations increase.

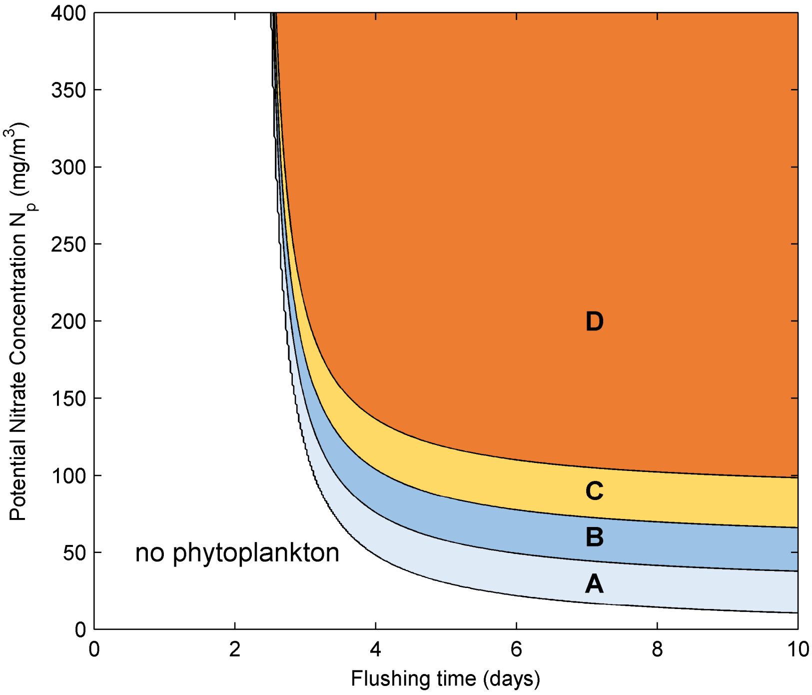

Figure 10-1: ETI susceptibility bandings for phytoplankton based on flushing time and potential nitrogen concentration. This graph shows model output based on assumed nitrogen half-saturation coefficient of 35 mg/m^3 and a net specific growth rate of 0.43 day^{-1}.

For the Avon Heathcote Estuary, the tuning parameter of *b* = 0.89 was previously determined (Plew, Zeldis et al. in review) based on output from a hydrodynamic model (Measures and Bind 2013). CLUES-Estuary provides volume and time-averaged predictions of potential nutrient concentrations, and mean tide, rather than spring tide, values are normally used to represent a typical tidal range. Volumes and tidal prism at mean tide are reported in Table 10-1.

The CLUES-Estuary approach calculates that the Avon-Heathcote Estuary has an average potential total nitrogen concentration of 306 mg/m^3, and a relatively long flushing time (5.6 days). These values indicate that the Avon Heathcote Estuary is moderately susceptible to macroalgae blooms (Band C) and highly susceptible to phytoplankton blooms (Band D). The high phytoplankton susceptibility indicates that high phytoplankton concentrations are likely to occur in the estuary. Indeed, ECAN water quality data revealed high concentrations of phytoplankton in this estuary (pers com. J. Zeldis, NIWA). However, the estuary's shallow depth, rapid vertical mixing and consequent moderate to high oxygen concentrations (stratification drives benthic oxygen reduction associated with excessive phytoplankton growth in deeper estuaries) indicate that these high phytoplankton concentrations are not likely to cause hypoxia. Eutrophication issues in shallow SIDE estuaries are predominantly driven by excessive macroalgal growth, rather than high phytoplankton concentrations (Robertson et al. 2016).

For Okains Bay and Le Bons Bay estuaries, the tuning factor *b* was derived (using equation 3) from inflow and salinity measurements collected along each estuaries during the field surveys (22-23 March 2017). The calculated value of *b* was then used to calculate dilution and concentrations of TN at other river flows.

Mean salinity in Okains Bay Estuary at high tide was 30.35 ppt, and ocean salinity was 34.22 ppt. This gives a dilution factor of D = 8.84. The riverine inflow at the time of the survey was 0.067 m^3/s, which matches closely to the NZRiverMaps predicted Mean Annual Low Flow (MALF, 0.055 m^3/s at the flow gauge site). We allow for additional inflow below the gauging site by scaling the measured inflow by the ratio of MALF at the gauging site to MALF at the lowest REC segment in the estuary. The scaled inflow is Q_F = 0.092 m^3/s. The tidal prism at the time of the survey was 172,000 m^3. The tuning factor, based on measured inflows, tidal prism and salinities was 0.81.

Estimates of eutrophication susceptibility were made using median TN concentrations and median inflows, and mean tidal range at the coast (1.65 m) allowing for a 5 per cent reduction in tidal range within the estuary.

The CLUES-Estuary approach indicates that, under median flow conditions, Okains Bay Estuary has a low susceptibility to macroalgal blooms (Band B). No significant macroalgal growth was observed at the time of the field surveys. This estuary's flushing time is too brief for significant estuarine phytoplankton growth, indicating that blooms are highly unlikely (Band A).

At Le Bons Bay the inflow was 0.080 m^3/s, and the tidal prism at the time of the survey was 31,170 m^3 (water levels between 0 m and 0.45 m). Mean salinity was 29.00 ppt, giving a dilution of D = 6.56. The tuning parameter b = 0.32. The estuary's minimum water level was set to 0 m, and the high tide level was set 0.82 m (20 per cent below MHW) for calculating the volumes and tidal prism. Estimates of eutrophication susceptibility were made using mean TN concentrations and median river inflows.

Le Bons Bay Estuary has a low vulnerability to macroalgal blooms (CLUES-Estuary Band B), with no significant macroalgal growth observed during field surveys. Under typical summer conditions, river inflows will be mostly below median flow, consistent with this low susceptibility and banding. Phytoplankton blooms are highly unlikely (Band A) in this estuary because its flushing time is too brief for any appreciable concentrations to develop.

Table 10-2: CLUES-Estuary estimate of eutrophication susceptibility. Based on the (Plew, Zeldis et al. in review) CLUES-Estuary tool. Data for Avon-Heathcote Estuary were derived from Burge (2007); those for Okains Bay and Le Bons Bay were derived from NIWA's NZRiverMaps.

Estuary	Inflow (m^3/s)	Volume at MHW (m^3)	Tidal Prism mean (m^3)	Return flow/ mixing factor	Dilution factor	Mean salinity (ppt)	Flushing time (days)	Inflow nitrogen conc. (mg/m^3)	Ocean nitrogen conc. (mg/m^3)	Estuary potential nitrogen conc. (mg/m^3)	Macroalgae band	Phytoplankton band
Avon-Heathcote	2.47	9,412,000	7,006,000	0.89	7.9	30.0	5.6	2,182	34.7	306	C	D
Okains Bay	0.167	247,050	246,100	0.81	7.1	29.4	2.4	595	34.7	113	B	A
Le Bons Bay	0.185	68,063	54,125	0.32	5.11	27.5	0.8	464	34.7	119	B	A

11 Comparison of susceptibility metrics with observed estuarine state

According to ETI tool 1, the ecological qualities expected from SIDE type estuaries, like the Avon-Heathcote, and Le Bons Bay estuaries that have a high combined ASSETS physical and N-load susceptibility are:

1. Moderate stress on ecosystems caused by the indicator exceeding preference levels for some species and a risk of sensitive species being lost or reduced.
2. Moderate macroalgal growth.

The ecological qualities expected from SIDE type estuaries like the Okains Bay Estuary, that have a moderate combined ASSETS physical and N-load susceptibility are:

1. A minor stress on sensitive biota caused by the indicator.
2. Some eutrophic symptoms (e.g. macroalgae) but still support for healthy seagrass and fish communities.

These points are consistent with the state of the Avon-Heathcote Estuary, which has moderate macroalgal growth (substantially reduced since diversion of wastewater effluent to the ocean; (Barr, N , Scheuer et al. 2017 in prep). The CLUES-Estuary approach predicted a macroalgae susceptibility band of C, indicating moderate impact, for the Avon-Heathcote Estuary. We note that under loading conditions prior to the diversion of the wastewater discharge, the Avon-Heathcote Estuary was placed in Band D for combined ASSETS physical and N-load susceptibility, and in Band D (high) for both macroalgae and phytoplankton using the CLUES-Estuary approach. The subsequent, post-diversion shift to Band C for combined ASSETS physical and N-load susceptibility, and Band C for macroalgae using the CLUES-Estuary approach is supported by recent studies showing large reductions in macroalgal biomass and biochemical indicators of eutrophication (Barr, N , Scheuer et al. 2017 in prep), and large reductions in benthic microalgal biomass (Zeldis, Depree et al. 2017 in prep) within the estuary. Barr, N , Scheuer et al. (2017 in prep) shows changes in internal nitrogen pools of the main bloom-forming macroalga, *Ulva sp*. in the Avon-Heathcote Estuary following the wastewater diversion. These changes suggest a relatively rapid, but only partial recovery of the trophic state of the estuary.

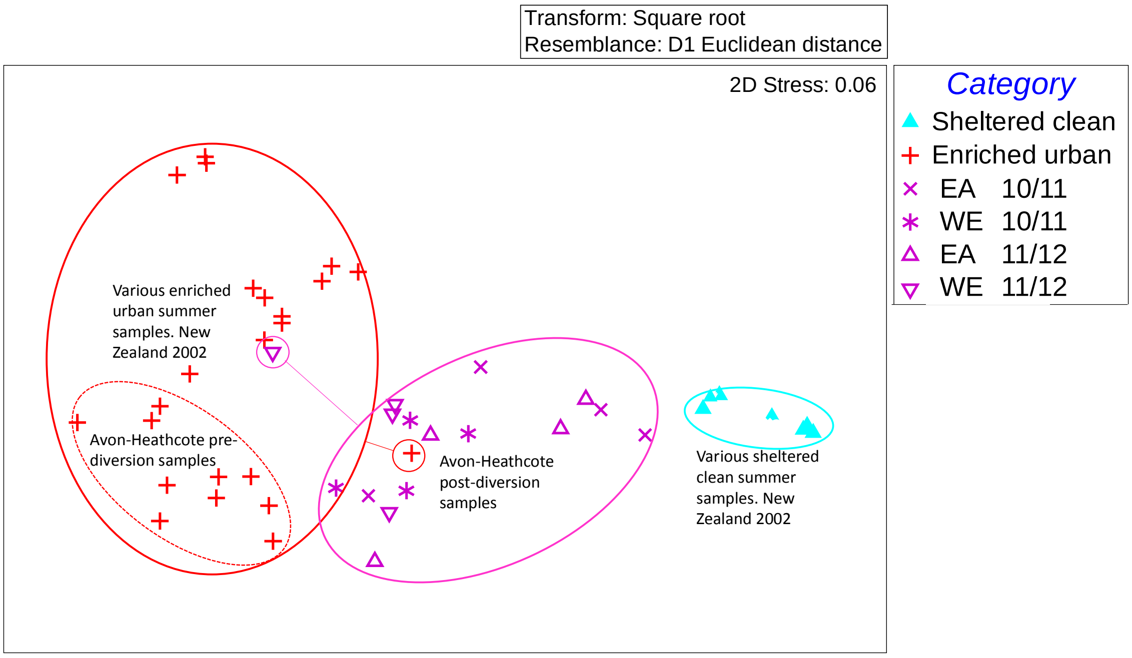

Figure 11-1: Multi-dimensional scaling (MDS) of N-indices in *Ulva* derived from Barr, Neill G, Dudley et al. (2013) for sites around New Zealand divided into two environmental categories, compared to the same N-indices in post-diversion Avon-Heathcote Estuary. Figure from (Barr, N , Scheuer et al. 2017 in prep). The MDS examines the similarity/dissimilarity between macroalgal samples from different locations around New Zealand. The blue grouping shows sheltered, clean sites from a 2002 survey of New Zealand estuaries, while the red grouping shows sites from nutrient-enriched, urban estuaries (including the pre-diversion Avon-Heathcote). The centre (pink) grouping shows samples from Avon-Heathcote Estuary post-diversion (2010/11 and 2011/12). Nine *Ulva* tissue N-indices used in the MDS similarity matrix were aspartate, glutamate, asparagine, glutamine, proline, and total remaining free amino acids, total chlorophyll (*a*+*b*), tissue-N and tissue-δ^{15}N.

There was little evidence of macroalgal growth in Okains Bay or Le Bons Bay estuaries during field surveys. The ASSETS approach was developed for large estuarine systems, and small estuaries with volumes less than 2.8 million m^3 do not fit within the bandings for dilution potential. In this report we assigned Okains Bay and Le Bons Bay estuaries a low dilution potential despite them falling outside of the size criteria. In the authors' opinion, ASSETS is inappropriate for small SIDE estuaries, and we recommend instead the CLUES-Estuary approach. We note that that both Okains Bay and Le Bons Bay Estuaries fit within the CLUES-Estuary Band B for macroalgae, and that this consistent with the absence of extensive macroalgal populations/biomass in these estuaries when we conducted bathymetric surveys.

We conclude that the ETI tools employed give a good indication of ecological condition in the three estuaries surveyed. However, we note that ETI tool 1 is intended only to enable the prioritisation of estuaries for more rigorous monitoring and management, and baseline ecological monitoring may be appropriate for Le Bons Bay Estuary and Okains Bay Estuary, particularly if changes to catchment N loading or freshwater flows are anticipated.

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