Estuarine Trophic Index Susceptibility Screening
for Hawke's Bay

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Executive summary

The susceptibility of six Hawke's Bay estuaries to eutrophication was assessed in a desktop study, using approaches developed within the New Zealand Estuary Trophic Index (ETI). The susceptibility assessment uses flow and nutrient load data obtained from catchment models and estimates of estuary physical properties obtained from a variety of sources. Limited data from two estuaries (salinity and chlorophyll-*a* observations from Ahuriri and Waitangi estuaries) were available for comparison, but otherwise the predictions have not been validated with field data. The results of this study should be considered as a screening step to identify which estuaries to prioritise for further investigations.

The eutrophication susceptibilities of the estuaries are given in bands A (low), B (moderate), C (high) and D (very high). In bands A and B, estuary health is expected to be good, with a low risk of symptoms of eutrophication such as excessive macroalgal or phytoplankton growth, good sediment conditions (good oxygenation and low organic enrichment) and healthy macrobenthic animal communities. As the susceptibility increases to band C, macroalgal and phytoplankton blooms are more likely to occur, with associated reductions in sediment conditions, macrobenthic community health and deteriorating water quality. In band D, there is a very high likelihood of eutrophic conditions within an estuary, and the health of the estuary is expected to be poor. The susceptibilities of the estuaries are shown in Figure 1.

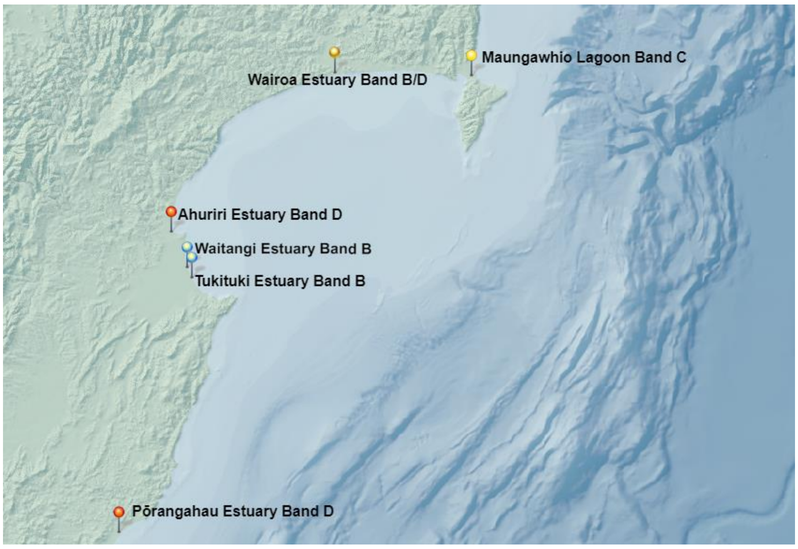

Figure 1: Susceptibility bands of the six estuaries. Susceptibility bands indicate the expected level of eutrophication in the estuary, and are A = low, B = moderate, C = high, and D = very high.

Ahuriri Estuary and Pōrangahau Estuary have very high eutrophication susceptibilities and are considered likely to have severe eutrophic conditions present according to this screening study. Ahuriri Estuary is predicted to be susceptible to both macroalgal and phytoplankton blooms, consistent with high observed chlorophyll-*a* concentrations. Maungawhio Lagoon is predicted to have high susceptibility and is expected to show some impact of excess macroalgal and potentially phytoplankton growth.

Wairoa, Waitangi and Tukituki estuaries all have riverine-like estuaries with high river flow, short flushing times and limited intertidal area, characteristics that generally reduce the susceptibility of estuaries to high nutrient loads. These three estuaries are predicted to have a moderate susceptibility to eutrophication. However, Wairoa River has a large lagoon near the mouth that may be more susceptible to eutrophication than the main river channel, and this area of the estuary has a very high eutrophication susceptibility. Tukituki Estuary receives very high nutrient loads and could be prone to phytoplankton or macroalgal blooms during extended low flow periods. Under usual flows, the short flushing time and low salinity are expected to restrict algal growth. Waitangi Estuary is similar, with high flows and short flushing times expected to limit macroalgal and phytoplankton growth. This estuary has multiple arms, and observations show that water is brackish (salinity of ~5 ppt), with moderate to high chlorophyll-*a* concentrations although it is not clear whether this is from estuarine phytoplankton or from algal matter in the river inflows. There may be parts of the estuary where eutrophic conditions develop, but the overall susceptibility is predicted as moderate.

1 Introduction

Hawke's Bay Regional Council (HBRC) requested a screening study of six estuaries (Figure 1-1) to determine their likely susceptibility to eutrophication (enrichment of nutrients, leading to excessive growth of primary producers including nuisance macroalgae and phytoplankton). This information will assist HBRC in determining if and where further investigations should be targeted.

The six estuaries (Figure 1-1) are

- Maungawhio Lagoon
- Wairoa Estuary
- Ahuriri Estuary
- Waitangi Estuary
- Tukituki Estuary
- Pōrangahau Estuary.

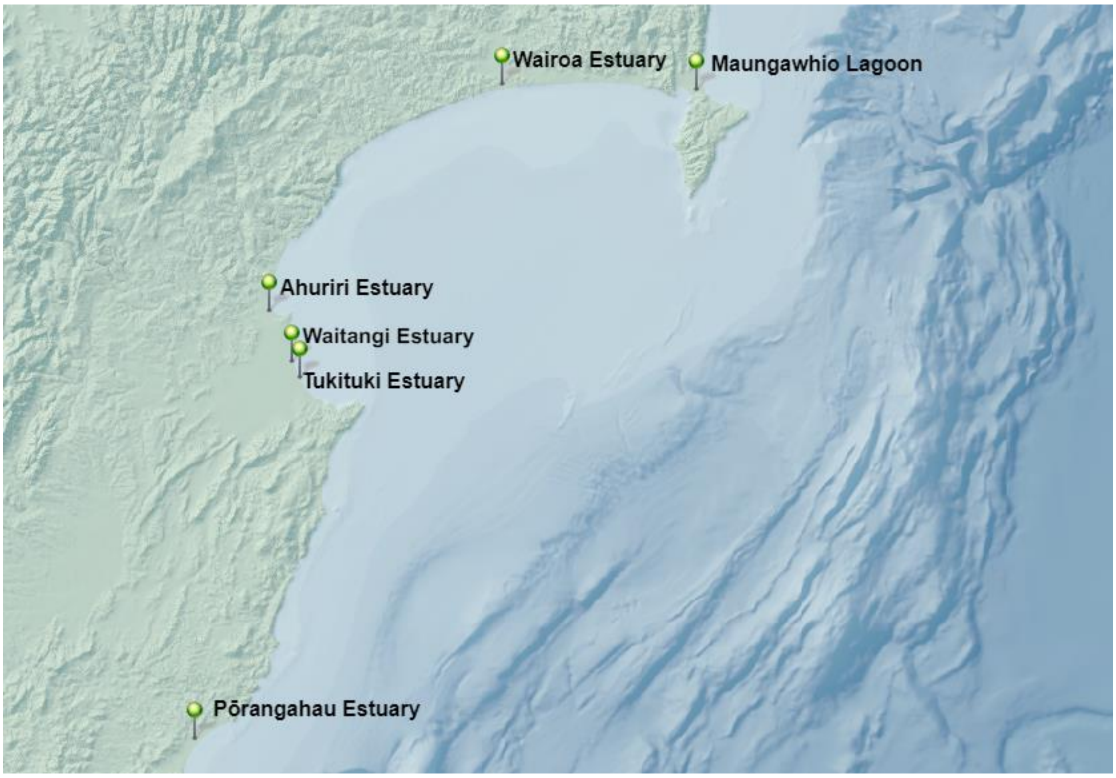

Figure 1-1: Locations of the six estuaries where susceptibility to eutrophication is calculated.

The susceptibilities of the six estuaries to nutrient loads are assessed using three approaches that are part of the New Zealand Estuary Trophic Index (ETI) tool box for assessing the risk to and health of New Zealand estuaries (Zeldis et al. 2017a; Zeldis et al. 2017c; Zeldis et al. 2017d). The three approaches are:

1. **Assessment of Estuary Trophic Status (ASSETS):** this method was originally developed for large northern American estuaries (Bricker et al. 2003) and has been modified for New

Zealand conditions within ETI tool 1 (Robertson et al. 2016a). ASSETS is best suited for large estuaries. ASSETS uses a combination of physical characteristics (volume and freshwater flushing) and areal loading rate (mg N/m^2/d) to determine the susceptibility of an estuary to nutrient loads.

2. **Dilution Modelling Approach:** the dilution modelling approach was developed to address some of the limitations of ASSETS and is well suited to the smaller estuaries typically found in New Zealand. The dilution modelling approach uses simple mixing models to estimate nutrient concentrations within, and flushing times of, estuaries which in turn are used to predict the response of macroalgae and phytoplankton (Plew et al. 2020b). The dilution modelling approach is included in ETI tool 1, alongside ASSETS https://shiny.niwa.co.nz/Estuaries-Screening-Tool-1/

3. **Estuary Bayesian Belief Network (BBN)**: ETI tool 3 is a Bayesian Belief Network that predicts an ETI score based on estuary properties, nutrient and sediment loads. The BBN also provides estimates of estuary health indicators, and can be combined with observations of those indicators to refine the ETI score (Zeldis and Plew in prep).

2 Estuary types and properties

The six estuaries (Figure 1-1) are classified according to the New Zealand Coastal Hydrosystems (NZCHS) typology (Hume et al. 2016) and the New Zealand Estuary Trophic Index (ETI) typology (Hume 2018a; Robertson et al. 2016a) based on their geomorphic and hydraulic properties. The NZCHS typology has eleven classes, many of which contain subclasses. The ETI has only four classes: Deep Subtidal Dominated Estuaries (DSDE), Shallow Intertidal Dominated Estuaries (SIDE), Shallow Short Residence Time Tidal River Estuaries (SSRTRE), and Coastal Lakes. Descriptions of the six estuaries are given below, in order from north to south.

2.1 Maungawhio Lagoon

The northern most estuary, Maungawhio Lagoon, is located at the base of the Mahia Peninsula (Figure 2-1). It is considered to have high conservation and cultural values, supporting a variety of birdlife and mahinga kai. Under the NZCHS typology, Maungawhio Lagoon is a 7A Tidal Lagoon (permanently open). According to the Coastal Explorer database the estuary has 78.7% intertidal area. With a mean freshwater flow (over a tidal period) to volume ratio of 0.12, it can be classified as a SIDE according to the typology used in the ETI. It is small estuary of ~960,000 m^2, and in planform consists of a tidal lagoon that connects to the main Kopuawhara Stream channel approximate 1 km upstream of where the estuary discharges to the sea at Oraka Beach. The 74 km^2 catchment is largely pastoral with some shrub and exotic forestry in the upper catchment. The extent of the estuary is shown using the shape file associated with Coastal Explorer in Figure 2-1.

Figure 2-1: Maungawhio Lagoon. The estuary extent is based on the shape file from Coastal Explorer.

2.2 Wairoa Estuary

Wairoa Estuary lies adjacent the Wairoa township, and is a riverine type estuary with an attached lagoon east of the estuary mouth (Figure 2-2). It is classed as a 6B Shallow drowned valley under the NZCHS. The Wairoa Estuary has a high freshwater flow/volume ratio of 0.58 and low intertidal area (16% according to Coastal Explorer), thus is classified as an SSRTRE according to the ETI typology. The extent of the estuary shown in Figure 2-2 is based on Coastal Explorer, thus the upstream extent is approximate. The estuary has the largest catchment of the six estuaries in this study (3,672 km^2) which is mostly pastoral and indigenous forest.

Figure 2-2: Wairoa Estuary. The estuary extent is based on the shape file from Coastal Explorer.

2.3 Ahuriri Estuary

Ahuriri Estuary is located on the northern outskirts of Napier (Figure 2-3). It has a catchment area of ~ 145 km^2, which is a mix of urban/industrial and pastoral. It is classified as a 7A Tidal lagoon (permanently open) according to the NZCHS. According to Coastal Explorer, it has a surface area of 2,746,000 m^2 of which 9.8% is intertidal. However, that estimate of intertidal area appears low, with estimates of 60% intertidal area reported elsewhere (https://www.napier.govt.nz/napier/reserves/ahuriri-estuary/). This disagreement may partially be caused by different interpretations of the extent of the estuary. With a low freshwater/volume ratio of 0.08 and likely high intertidal area, Ahuriri Estuary is classified as a SIDE according to the ETI typology.

Figure 2-3: Ahuriri Estuary. The estuary extent is based on the shape file from Coastal Explorer.

2.4 Waitangi Estuary

The Waitangi estuary lies south of Napier, just north of the Clive township (Figure 2-4). The Waitangi Estuary (called Ngaruroro Estuary in Coastal Explorer) receives flow from the Tutaekuri, Ngaruroro and Clive rivers. It is classified as a 6B Tidal river mouth (spit enclosed) estuary under the NZCHS. Coastal Explorer gives an estuary area of 718,800 m^2 and 0% intertidal area. There does appear to be some intertidal flat near where the Clive River joins the estuary, and the margins of the estuary are likely to be intertidal, so 0% clearly underestimates the intertidal portion of the estuary. The intertidal area does appear to be low, based on aerial imagery, but the actual intertidal area has not been estimated here. With a likely low intertidal area, and a high ratio of freshwater inflow to volume of 1.14, Waitangi Estuary is classified as a SSRTRE according to the ETI typology. The catchment area of ~3,369 km^2 is largely pasture, with scrub, indigenous forest and some tussock in the upper reaches. The mouth of the Waitangi Estuary is highly mobile, migrating along a ~ 1 km length of coast, and at times appears to be constricted (although not completely closed). The tidal range of the estuary likely reduces as the mouth constricts.

Figure 2-4: Waitangi Estuary. The estuary extent is based on the shape file from Coastal Explorer.

2.5 Tukituki Estuary

Tukituki Estuary is not included in Coastal Explorer, but its physical characteristics were summarised in a letter report by Hume (2013), and the approximate estuary extent digitised from Google Earth is shown in Figure 2-5. The catchment of the Tukituki Estuary is 2507 km^2 is mostly pastoral. The estuary has an area of ~225,600 m^2 and 28% intertidal area. It has a very high freshwater inflow/volume ratio of 8.4 and is classified as a SSRTRE in the ETI typology, and a 6B Tidal river mouth (spit enclosed) in the NZCHS. Like the Waitangi Estuary, the mouth of the Tukituki is high mobile, and the width of the mouth can vary between >120 m (e.g., 29 Sep 2018) and closed to the sea under low flows (e.g., 4 April 2015, 5 March 2013). As such, the Tukituki Estuary can be considered as an Intermittently Closed and Open Estuary (ICOE), a subtype of SIDEs or SSRTREs, in the ETI typology.

Figure 2-5: Tukituki Estuary. Estuary extent approximated from satellite imagery from 27/3/2018.

2.6 Pōrangahau Estuary

While Pōrangahau Estuary (Figure 2-6) is included in Coastal Explorer, the associated shape file and intertidal area (0%) do not match more recent satellite imagery. The estuary extent at high tide was re-digitised from Google Earth images from 4/8/2019 and the low tide extent from 27/8/2019. The revised estuary area is 3,426,500 m^2 with 81% intertidal area. The tidal prism was estimated from the areas at high and low tide, assuming that the tidal range within the estuary was 80% of that at the coast. Pōrangahau Estuary has a moderate freshwater flow/volume ratio of 0.27 and could be classified as either a SIDE or SSRTRE. The NZCHS classifies the estuary as 7A Tidal lagoon (permanently open), which more consistent with the ETI SIDE classification (Hume 2018b), which is used here. The 855 km^2 catchment is predominately pastoral.

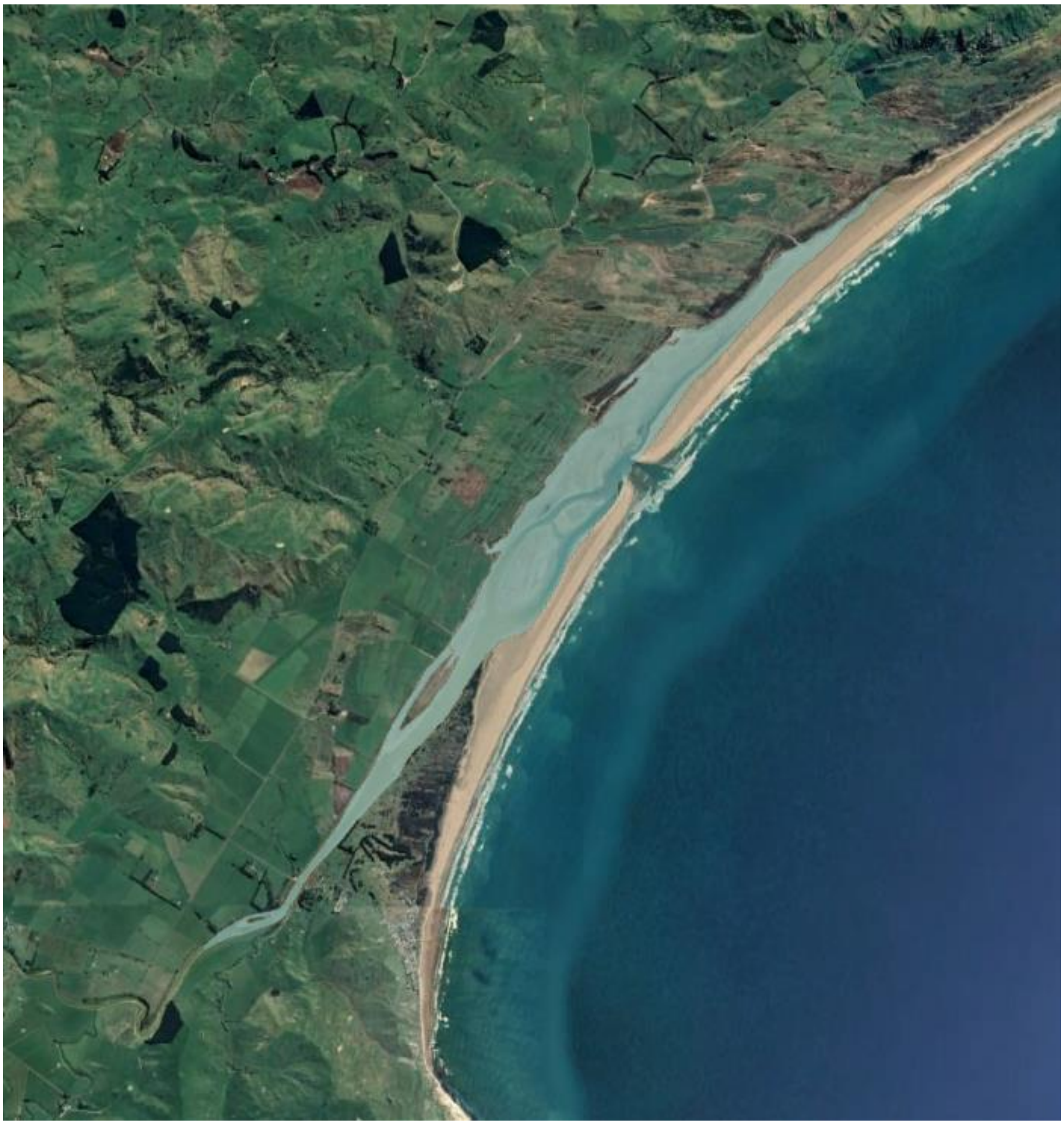

Figure 2-6: Pōrangahau Estuary. The estuary extent is based on satellite imagery from 4/8/2019.

3 Flow and nutrient loads

Annual total nitrogen (TN) and total phosphorus (TP) loads were obtained from the Catchment Land Use for Environmental Sustainability (CLUES) model (Elliott et al. 2016; Semadeni-Davies et al. 2020). CLUES is a steady state model that predicts the effect of land use and land management on water quality which is indicated by estimates of mean annual loads of nutrients (TP and TN), *E. coli* and sediment; only the nutrient loads were used in this study. The model first estimates loads generated by the sub catchment of each segment of the River Environments Classification, REC v2.4[1], stream network, these loads are then routed downstream to obtain instream cumulative loads. The total TN and TP loads to the estuaries were calculated as the sum of the loads discharged to the estuary via terminal (coastal) stream segments.

The ETI tool 1 dilution modelling approach and ETI tool 3 BBN include a seasonal adjustment when predicting phytoplankton response. This requires the February flow seasonality factor (ratio of February mean flow to annual mean flow), obtained from NZRiverMaps (Booker and Whitehead 2017; Booker and Woods 2014), and ratios of summer to annual nutrient concentrations in terminal reaches which were derived from Whitehead et al. (2019). Mean flows are also taken from NZRiverMaps. These data are summarised in Table 3-1.

Table 3-1: Mean flows, February flow seasonality, annual total nitrogen (TN), total phosphorus (TP) and load seasonality factors for the six estuaries.

Estuary	Mean flow (m^3/s)	Feb seasonality	TN (t/y)	TN seasonality	TP (t/y)	TP seasonality
Maungawhio Lagoon	1.753	0.595	48.44	0.705	10.39	0.819
Wairoa	124	0.560	2118	1.002	1035	1.285
Ahuriri Estuary	1.43	0.572	54.35	0.687	6.25	0.870
Waitangi Estuary	51.3	0.497	1393	0.551	362	0.731
Tukituki Estuary	45.9	0.465	1709	0.620	303	0.945
Pōrangahau Estuary	9.88	0.361	433	0.765	109	0.963

[1] https://niwa.co.nz/freshwater-and-estuaries/management-tools/river-environment-classification-0

4 ASSETS susceptibility assessment (ETI tool 1)

4.1 Flushing potential

Flushing potential indicates the ability of the river to flush the estuary and is calculated according to the ASSETS approach described in ETI tool 1. This approach defines an estuary's flushing potential as:

$$\text{daily freshwater inflow } (m^3/d) \text{ / estuary volume } (m^3). \quad (1)$$

Estuaries can then be classified using the resulting value as having a high, moderate or low flushing potential. All six estuaries are mesotidal (0.8 m to 1.8 m range) with corresponding flushing potential bands of 10^0-10^{-1} high, 10^{-2} moderate, 10^{-3}-10^{-4} low (Robertson et al. 2016a).

The Ahuriri Estuary has a moderate flushing potential, while the other five estuaries have high flushing potentials. The Tukituki Estuary has the highest flushing potential of 16.2 d^{-1}.

Table 4-1: Calculated flushing potentials for the six estuaries. Based on ETI tool 1 (Robertson et al. 2016a).

Estuary	Mean annual freshwater input (m^3/day)	Estuary volume at spring high tide (m^3)	Tidal range	Flushing potential (day^{-1})	Flushing potential band
Maungawhio Lagoon	212,232	1,034,215	1.426	0.21	High
Wairoa	10,808,498	9,734,901	1.48	1.1	High
Ahuriri Estuary	123,811	6,347,333	1.471	0.020	Moderate
Waitangi Estuary	5,478,674	2,485,690	1.458	2.20	High
Tukituki Estuary	3,964,291	244,708	1.458	16.2	High
Pōrangahau Estuary	853,695	2,522,582	1.366	0.34	High

4.2 Dilution potential

Dilution potential indicates the capacity for the estuary to dilute incoming riverine sources. The ASSETS approach defines dilution potential as:

$$\text{1/estuary volume (cubic feet)} \quad (2)$$

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 bands are 10^{-12}-10^{-13} high, 10^{-11} moderate, 10^{-9}-10^{-10} low.

The Wairoa Estuary and Ahuriri Estuary have low dilution potentials, but the volumes of the other four estuaries are too small for their dilution potentials to be categorised under the ASSETS approach (Table 4-2). Here, they are assigned *"very low"* dilution potentials.

Table 4-2: Calculated flushing potentials for the six estuaries. Based on ETI tool 1 (Robertson et al. 2016a).

Estuary	Estuary volume (ft^3)	Dilution potential ($1/ft^3$)	Dilution potential band
Maungawhio Lagoon	36,522,966	2.74×10^{-08}	*Very low*
Wairoa Estuary	343,784,811	2.91×10^{-09}	Low
Ahuriri Estuary	224,153,950	4.46×10^{-09}	Low
Waitangi Estuary	87,781,312	1.14×10^{-08}	*Very low*
Tukituki Estuary	8,641,781	1.16×10^{-07}	*Very low*
Pōrangahau Estuary	89,084,140	1.12×10^{-08}	*Very low*

4.3 Physical susceptibility

The flushing potential and dilution potential scores are combined to determine the physical susceptibility of an estuary using the ASSETS categories (Table 4-3).

Table 4-3: ASSETS physical susceptibility classification system for shallow intertidal-dominated estuaries (SIDE) and shallow short residence time tidal river and tidal river-lagoon estuaries (SSRTRE). Table from ETI tool 1 (Robertson et al. 2016a).

		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

As noted in 4.2, the small volumes of four of the estuaries resulting in dilution potentials outside of the ranges covered in the ASSETS approach. *Very low* dilution potentials were assigned to these estuaries. The same four estuaries had high flushing potentials, and the ASSETS classification does not cover a combination of high flushing potential and very low dilution potential. Here it is assumed, by inference from Table 4-3, that this combination will result in a high physical susceptibility.

Five of the six estuaries have a high physical susceptibility, under the ASSETS approach. Ahuriri Estuary has a moderate flushing potential (a consequence of its small freshwater inflow relative to its size) but low dilution potential, resulting in a high physical susceptibility according to ASSETS (Table 4-3). Maungawhio Lagoon, Waitangi Estuary, Tukituki Estuary and Pōrangahau Estuary all have dilution potentials outside of the ASSET bandings (very low). The combination of high flushing potential and very low dilution potential is considered to result in a high physical susceptibility.

Wairoa Estuary has a moderate physical susceptibility under the ASSETS approach, the lowest of the six estuaries considered in this evaluation.

Table 4-4: Calculated physical susceptibilities for the six estuaries. Based on ETI tool 1 (Robertson et al. 2016a). Entries marked with * have dilution potentials outside the bands defined in ASSETS.

Estuary	Flushing potential band	Dilution potential band	Physical susceptibility
Maungawhio Lagoon	High	*Very low**	*High**
Wairoa Estuary	High	Low	Moderate
Ahuriri Estuary	Moderate	Low	High
Waitangi Estuary	High	*Very low**	*High**
Tukituki Estuary	High	*Very low**	*High**
Pōrangahau Estuary	High	*Very low**	*High**

We note that the ASSETS approach was developed for large estuaries, and often appears to under-estimate the physical susceptibility of smaller, strongly intertidal estuaries. Hence, we recommend also considering the dilution model-derived calculation of eutrophication susceptibility for this estuary (see section 5 below).

4.4 Nutrient load susceptibility

ASSETS nutrient load susceptibilities are categorised from areal TN loads (Table 4-5). The ETI adaption of the ASSETS approach notes that for SSRTREs with no “high risk” features, the appearance of eutrophic conditions is unlikely bellow an N-load <2000 mg N/m^2/d (although the confidence in this threshold is low (Robertson et al. 2016a). For SIDEs and SSRTREs with “high risk” features, the bandings are:

- Very high >250 mg/m^2/d
- High: >50 – 250 mg/m^2/d
- Moderate: 10 – 50 mg/m^2/d
- Low: <10 mg/m^2/d

High risk features include:

- deep, poorly flushed, holes and/or stratified basins/channels
- banks or beds lined with stable substrate for attachment of nuisance macroalgal growths
- significant areas of tidal flats or shallow channel margins where muds can settle and opportunistic macroalgae can grow (e.g. a tidal river with an adjoining lagoon).

Maungawhio Lagoon is classified as a SIDE and receives a high areal TN load of 138 mg/m^2/d.

Wairoa Estuary can be considered to be either an SSRTRE with adjoining lagoon (a high risk feature) or a SIDE. It receives a very high TN load of 2,320 mg/m^2/d.

Ahuriri Estuary has also been classified as a SIDE and receives the lowest N load of 54 mg/m^2/d. This is at the lower end of the "high" TN load susceptibility band.

Waitangi Estuary is a SSRTRE with very little intertidal area (mostly near the mouth) and does not appear to have high risk features. However, the TN-load of 5,310 mg/m^2/d exceeds the suggested 2,000 mg/m^2/d threshold for SSRTRE, so a "very high" band has been applied.

Tukituki Estuary is also an SSRTRE but appears (from aerial imagery) to have more intertidal and shallow areas near the mouth. The Tukituki Estuary has an extremely high TN load of 20,750 mg/m^2/d so a "very high" TN load susceptibility band is applied.

Pōrangahau Estuary has been classified as a SIDE due to its long, extended lagoon. The TN load of 524 mg/m^2/d places this estuary in the very high susceptibility band.

Table 4-5: Areal N-load susceptibility for the six estuaries under current TN loads. Based on Robertson et al. (2016a) ETI tool 1.

Estuary	Estuary Type	Sum of mean annual TN-loads - all tributaries (kg/year)	Estuary surface area at high water spring (m^2)	Areal TN load (mg/m^2/day)	TN load susceptibility band (ETI tool 1)
Maungawhio Lagoon	SIDE	48,435	959,805	138	High (>50-250 mg/m^2/d)
Wairoa Estuary	SSRTRE	2,118,390	2,498,812	2320	Very High (>250 mg/m^2/day)
Ahuriri Estuary	SIDE	54,346	2,745,765	54	High (>50-250 mg/m^2/d)
Waitangi Estuary	SSRTRE	1,392,700	718,823	5310	Very High (>250 mg/m^2/day)
Tukituki Estuary	SSRTRE	1,709,484	225,650	20,750	Very High (>250 mg/m^2/day)
Pōrangahau Estuary	SIDE	433,133	3,426,500	346	Very High (>250 mg/m^2/day)

4.5 Combined physical and nutrient load susceptibility

According to the ASSETS approach in ETI tool 1, physical susceptibility and TN load susceptibility are combined to calculate a combined physical and nutrient load susceptibility, as shown in Table 4-6.

Table 4-6: Combined physical and nutrient load susceptibility bandings for shallow intertidal-dominated estuaries. Table from ETI tool 1 (Robertson et al. 2016a).

Physical susceptibility	TN load susceptibility ($mg/m^2/day$): 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

According to the ASSETS approach, Maungawhio Lagoon and Ahuriri Estuary are classed as having high combined physical and nutrient load susceptibility (band C), while Wairoa Estuary, Waitangi Estuary, Tukituki Estuary and Pōrangahau Estuary all have very high combined physical and nutrient load susceptibility (band D).

Table 4-7: Combined physical and nutrient load susceptibility for the six estuaries under current TN loads. Based on Robertson et al. (2016a) ETI tool 1. Entries marked with * have dilution potentials outside the bandings defined in ASSETS.

Estuary	Physical susceptibility	TN load susceptibility band (ETI tool 1)	Combined physical and nutrient load susceptibility
Maungawhio Lagoon	*High**	High	Band C High*
Wairoa Estuary	Moderate	Very High	Band D Very High
Ahuriri Estuary	High	High	Band C High
Waitangi Estuary	*High**	Very High	Band D Very High*
Tukituki Estuary	*High**	Very High	Band D Very High*
Pōrangahau Estuary	*High**	Very High	Band D Very High*

5 Estuary Trophic Index susceptibility (ETI tool 1)

5.1 Background to the ETI dilution modelling approach

Because the ASSETS approach employed in the ETI tool was developed for large, mostly sub-tidal estuaries in the United States, it often under-estimates susceptibility of New Zealand estuaries, particularly for small estuaries with volumes <2.8 million m^3 (Robertson et al. 2016a, page 30). A dilution modelling approach (Plew et al. 2018) was also developed within the ETI 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 (Plew et al. 2020b; Zeldis et al. 2017b) (Table 5-1).

The dilution modelling approach predicts the average potential nutrient concentrations in the estuary. Potential nutrient concentrations are those that would occur in the absence of nutrient sources or sinks in the estuary, such as uptake into algae or losses through denitrification. Potential concentrations are expected to be higher than observed concentrations, because observed concentrations show the remaining nutrients in the water column after some have been removed or taken up. Potential nutrient concentrations are a stronger indicator of eutrophication susceptibility than observed values because much of the supplied N is taken up into algal biomass (Plew et al. 2020b; Plew et al. 2018).

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

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

The expected condition of the estuary for each band is described in Table 5-1. The thresholds between each band are based on a comparison of potential concentrations with observations of opportunistic macroalgae from 21 New Zealand estuaries (Plew et al. 2020b). Observations of macroalgal impact were taken in summertime, while the potential nitrogen concentrations were calculated from annual nitrogen loads and mean flow. The thresholds between bandings should not be regarded as absolute, rather they are indicative of shifts along a continuum of eutrophic state. The thresholds between the concentration bands are indicative of where transitions between these ecological conditions are expected. Other factors may influence the macroalgal response in an estuary besides nutrient load, for example the availability of suitable substrate for macroalgal growth and bioavailability of nutrients (e.g., the dissolved vs particulate ratios in the TN and ammonium-to-nitrate ratios), so the thresholds between concentration bands should be considered as indicative rather than absolute.

The macroalgal susceptibility bands are derived from macroalgal Ecological Quality Ratings (EQR) (Water Framework Directive - United Kingdom Advisory Group 2014) collected mostly from SIDEs where there are extensive intertidal flats where macroalgae can grow and accumulate. However the same bandings have been found to be a good proxy for overall ETI score in estuaries where other factors may limit the accumulation of macroalgae, such as substrate or high currents that scour or detach macroalgae (Plew and Dudley 2018a; Plew and Dudley 2018b; Plew et al. 2020a). Common secondary eutrophication symptoms observed include poor sediment oxygenation driven by enhanced benthic microbial activity, microphytobenthos, and increased muddiness. Consequently, the ETI macroalgal susceptibility band is also indicative of other benthic impacts.

Macroalgae are seldom limited by phosphorus (P). Measurements of tissue nitrogen and phosphorus have found that macroalgae can accumulate nitrogen well above the molar Redfield ratio of N:P = 16:1, with values in excess of 60:1 reported (Atkinson and Smith 1983; Fong et al. 1994; Lourenço et al. 2007). Recent experiments show that phosphorus saturation concentration for *Agarophyton* (formerly *Gracilaria*) (the concentration at which further increases in phosphorus have no effect on growth rates) is much lower than that for nitrogen (B. Dudley, pers. com.). This means that macroalgae can extract P from the water column even when concentrations are low. The high tissue molar N:P ratios also demonstrates this capacity for growth at very low P availability. Thus, it is appropriate to develop bandings based on nitrogen.

However, P-limitation is possible in estuaries. Phytoplankton are typically P-limited when molar TN:TP > 50 and N-limited when TN:TP < 20 (Guildford and Hecky 2000). Either nutrient can be limiting for values between 20 and 50. Macroalgae have much higher tissue N:P than phytoplankton (Atkinson and Smith 1983), so P-limitation would occur at higher TN:TP ratios for macroalgae. Evidence-based bandings for susceptibility based on TP for P-limited growth have not yet been developed for estuarine macroalgae. In this report, a check for the *possibility* of P-limited growth is made by assuming P limitation is possible at molar TN:TP >60:1 which is equivalent to 27 g TN: 1 g TP. In many systems, testing of the tissue of primary producers (e.g., macroalgae and phytoplankton) is required to establish which nutrient is limiting to growth (Lapointe et al. 1992). Which primary nutrient limits growth may also vary in time (e.g., between spring and summer) (Fisher et al. 1992) so for systems where P-limitation is suspected, management of both N and P to limit eutrophication may be required.

Susceptibility to phytoplankton blooms are determined from potential TN and TP concentrations and flushing time using a growth model (Figure 5-1) that includes P (Plew et al. 2020b). While the majority (80%) of New Zealand's estuaries that are susceptible to phytoplankton blooms are N-limited (Plew et al. 2020b), as noted above, P can be growth-limiting at N:P molar ratios of > ~20:1. The growth model is used to estimate the potential chlorophyll-*a* (chl-*a*) concentration, which represents the maximum likely chl-*a* concentration that is likely to occur based on the available nutrients and flushing time. This concentration is related to a susceptibility band as reported in Table 5-1. The growth model shows that estuaries with short flushing times (<3.3 days) are highly unlikely to have phytoplankton blooms as they are flushed from the system faster than they can grow.

Table 5-1: Description of ecological quality for macroalgal and phytoplankton bandings. Adapted from ETI tool 2 (Robertson et al. 2016b) and Plew et al. (2020b). The bandings for predicted chl-*a* are for meso/polyhaline estuaries, defined as estuaries with salinities between 5-30 ppt.

Band	A Minimal eutrophication	B Moderate eutrophication	C High eutrophication	D Very high eutrophication
Opportunistic Macroalgae	$TN_{est} < 80$ mg/m^3 Ecological communities (e.g., bird, fish, seagrass, and macroinvertebrates) are healthy and resilient. Algal cover <5% and low biomass (<100 g/m^2 wet weight) of opportunistic macroalgal blooms and with no growth of algae in the underlying sediment. Sediment quality high.	$80 \leq TN_{est} < 200$ mg/m^3 Ecological communities (e.g., bird, fish, seagrass, and macroinvertebrates) are slightly impacted by additional macroalgal growth arising from nutrients levels that are elevated. Limited macroalgal cover (5–20%) and low biomass (100–200 g/m^2 wet weight) of opportunistic macroalgal blooms and with no growth of algae in the underlying sediment. Sediment quality transitional.	$200 \leq TN_{est} < 320$ mg/m^3 Ecological communities (e.g., bird, fish, seagrass, and macroinvertebrates) are moderately to strongly impacted by macroalgae. Persistent, high % macroalgal cover (25–50%) and/or biomass (>200–500 g/m^2 wet weight), often with entrainment in sediment. Sediment quality degraded.	$TN_{est} \geq 320$ mg/m^3 Ecological communities (e.g., bird, fish, seagrass, and macroinvertebrates) are strongly impacted by macroalgae. Persistent very high % macroalgal cover (>75%) and/or biomass (>500 g/m^2 wet weight), with entrainment in sediment. Sediment quality degraded with sulphidic conditions near the sediment surface.
Phytoplankton	chl-*a* < 5 µg/l Ecological communities are healthy and resilient.	5 ≤ chl-*a* < 10 µg/l Ecological communities are slightly impacted by additional phytoplankton growth arising from nutrients levels that are elevated.	10 ≤ chl-*a* < 16 µg/l Ecological communities are moderately impacted by phytoplankton biomass elevated well above natural conditions. Reduced water clarity likely to affect habitat available for native macrophytes.	chl-*a* ≥ 16 µg/l Excessive algal growth making ecological communities at high risk of undergoing a regime shift to a persistent, degraded state without macrophyte/seagrass cover.

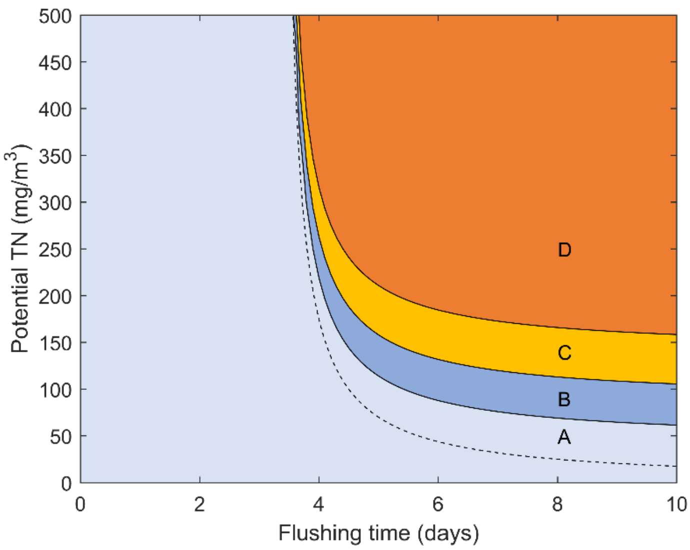

Figure 5-1: ETI susceptibility bandings for phytoplankton based on flushing time and potential total nitrogen concentrations. This graph shows model output based on an assumed half-saturation coefficient of 35 mg/m^3 TN and a net specific growth rate of 0.3 day^{-1} for the case when phosphorus is not limiting. The solid curves indicate thresholds between ETI bandings, and below the dashed line phytoplankton are flushed from the estuary faster than they grow.

The dilution modelling approach uses simple models to account for the mixing between the inflowing river and sea waters, providing an estimate of the potential nutrient concentration in the estuary averaged over time and space. While multiple compartment models, which provide some spatially resolved predictions, have been developed for other New Zealand estuaries (Plew and Dudley 2018a; Plew et al. 2019; Plew et al. 2020a), these require salinity and bathymetry data not available at this time for Hawke's Bay estuaries and are better suited for more refined investigations in the future.

5.2 ETI tool 1 inputs

The ETI tool 1 dilution modelling approach estimates potential TN concentrations and estuary flushing time using tidal prism (spring tide), volume at high tide, freshwater inflow, and nutrient (TN) load. Macroalgal susceptibility is calculated using mean flow and annual TN load. Macroalgae are sensitive to annual loads because overwintering plants respond early in the production season on timescales of weeks/months. In contrast, phytoplankton response is immediate, on the order of days. As effects of phytoplankton blooms are usually more common in summer, the phytoplankton susceptibility is calculated for summer flow and nutrient concentrations. The input data were obtained from variety of sources:

- Estuary tidal prism, volume – Coastal Explorer (Hume et al. 2016; Hume et al. 2007)
- Annual nutrient loads and mean flows – CLUES (Elliott et al. 2016; Semadeni-Davies et al. 2020)
- February flow seasonality factor – NZRiverMaps (Booker and Whitehead 2017; Booker and Woods 2014)
- Summer/Winter nutrient load ratios - Whitehead et al. (2019).

Dilution models are more accurate if they can be tuned using salinity data. HBRC provided conductivity data for the Ahuriri and Waitangi Estuaries, which has been used to approximate volume-averaged salinities for these estuaries (Table 5-2). Conductivities (specific conductance) were converted to practical salinity (S) using the Gibbs Seawater Oceanographic Toolbox of TEOS-10 for matlab[2]

Salinities were averaged across all sites within an estuary, and the estuary dilution factor D calculated as

$$D = \frac{S_o}{S_o - S} \qquad (3)$$

Where S_o = 35.05 is the ocean salinity for the region, obtained from the CSIRO Altas of Regional Seas climatology (CSIRO 2011). Note that 1/D is the fraction of freshwater in the estuary, so Ahuriri Estuary has approximately 44% freshwater content, while Waitangi Estuary has 86% freshwater content.

An estuary tuning parameter b can be calculated from the dilution factor (Plew et al. 2018)

$$b = \frac{QT\left(T - \frac{1}{2}\right) - P}{\frac{QT}{2} - P} \qquad (4)$$

Table 5-2: Conductivity observations from sites in the Ahuriri and Waitangi Estuaries, used to estimate the estuary dilution factors. Average conductivity (specific conductance) for each site were supplied by HBRC. Salinity for each site was estimated from conductivity and averaged across each estuary. The dilution factors were calculated assuming ocean salinity of 35.05.

Estuary	Site	Average conductivity (µS/cm)	Salinity	Dilution factor
Ahuriri Estuary	Quarantine Rd	15,416	8.98	
Ahuriri Estuary	Turfrey Road	26,643	16.30	
Ahuriri Estuary	Watchman Road	30,527	18.93	
Ahuriri Estuary	Woolshed Road	36,468	23.03	
Ahuriri Estuary	Pandora Bridge	47,659	31.02	
Ahuriri Estuary	**Average**		**19.65**	**2.276**
Waitangi Estuary	Clive River at Boat Ramp	9,048	5.05	
Waitangi Estuary	Waitangi Estuary at Mouth	8,112	4.49	
Waitangi Estuary	**Average**		**4.77**	**1.158**

[2] http://teos-10.org/pubs/gsw/html/gsw_contents.html

For the other estuaries, the dilution factor was calculated following Plew et al. (2018), where the dilution factor is calculated as a function of tidal prism *P*, freshwater inflow *Q*, tidal period *T* = 12.42 h and the estuary specific tuning factor *b*

$$D = \frac{P(1-b) + \frac{QT}{2}(1+b)}{QT} \quad (5)$$

The estuary tuning factors were estimated using an empirical relationship derived from observation and modelling across a range of estuaries (Plew 2020).

$$b = 0.952e^{-1.913\frac{QT}{P}} \quad (6)$$

5.3 ETI tool 1 results

Maungawhio Lagoon has a C-band (high) for susceptibility to macroalgae. The potential TN concentration of 295 mg/m^3 is approach the threshold between band C and D (320 mg/m^3) suggesting that the estuary may be on the transition between a healthy and eutrophic state. Due to the short flushing time of 3.2 days, phytoplankton blooms are not predicted to occur. However, should the flushing time increase to > 4 days, there is sufficient nutrient present to trigger phytoplankton growth concentrations of ~20 µg/l chl-*a*. In a mesotidal estuary (salinity ≥5 – 30), this would be at the lower end of band D (very high). Maungawhio Lagoon has a high intertidal area (78%) and is shallow, so phytoplankton blooms are less likely to result in poor water column oxygenation than in a deeper system, and the overall eutrophication risk is based on the macroalgal susceptibility. The overall susceptibility is high (band C) with macroalgae likely to be the dominant primary producer. However, there may be high phytoplankton concentrations, particularly in deeper, poorly flushed areas of the lagoon during period of low flow.

Wairoa Estuary is predicted to have high TN concentrations and poor exchange with the ocean (low salinity). The high TN concentration places this estuary in band D (very high) for macroalgal susceptibility, although the reduced salinity may reduce the area over which macroalgae become established. The estuary flushing time is too short (1.1 days) to support phytoplankton growth. With an intermediate intertidal area (16%), the overall susceptibility is determined by the worse of the macroalgal and phytoplankton bands. The overall susceptibility is very high (band D), with macroalgae likely to be dominant but growth may be restricted by low salinity.

Ahuriri Estuary has low freshwater inflow, but the nutrient concentrations of the inflow are high. The model predicts high TN concentrations in the estuary, placing this estuary in band D (very high) for macroalgal susceptibility. The flushing time is sufficient to support phytoplankton growth (36 days), and the phytoplankton model predicts that high chl-*a* concentrations could occur. The phytoplankton susceptibility is also band D. Coastal Explorer estimates the estuary to have 9% intertidal area, so both macroalgal and phytoplankton susceptibilities are considered. The overall susceptibility is very high (band D), with the estuary at risk of both macroalgal and phytoplankton blooms. The phytoplankton model predicts chl-*a* values of ~38 µg/l, which lies within the range of 90th percentile of observations in the upper estuary (Table 5-3)

Waitangi Estuary is predicted to be freshwater dominated (zero salinity) under mean flow conditions (this is how ETI tool 1 has been calibrated (Plew et al. 2020b)) and has low intertidal area. These characteristics mean that there is a low susceptibility (band A) to macroalgae. Observed salinities (Table 5-2) show brackish water is present in the estuary with 4.5 to 5.0. Salinities in this range imped the growth of common nuisance macroalgae in estuaries (Bews et al. 2021; Dawes et al. 1998; Dudley et al. submitted; Kumar et al. 2010; Rybak 2018). While ETI tool 1 likely underestimates the potential for macroalgal growth by underestimating salinity, wide-spread macroalgal booms do not appear highly probable, but the macroalgae susceptibility is increased to B to compensate for the underestimated salinities. The short flushing time (~1 day) means phytoplankton blooms are unlikely (band A). Observations show that moderate to high chl-*a* concentrations do occur in the estuary. These could either be during period of low flow, when the flushing time increases beyond ~4 days, or could result from non-estuarine (riverine) algae carried into the estuary by river flow. The overall susceptibility is low (band A) due to the low intertidal area but note that if intertidal area were greater than 5%, band B would be more appropriate.

Tukituki Estuary also has low predicted salinity (zero) and short flushing time (0.13 days) meaning the risk for both macroalgal and phytoplankton blooms are low (A-band). However, the nutrient concentrations are very high, and should the salinities be sufficient to support macroalgae, then blooms could occur in shallow or intertidal areas. The macroalgal susceptibility band is increased to B to allow for salinity being non-zero (but low) in the estuary. Overall, Tukituki Estuary is predicted to have a moderate eutrophication susceptibility (band B). However, the Tukituki Estuary is an ICOE that is observed to close to the sea during low river flows. When the estuary is closed to the sea, the flushing time will increase and any sea water in the estuary will likely be trapped in deep areas with stratification likely to develop unless the closure period is less than a few (3-5) days. Using the estuary volume from Coastal Explorer and Mean Annual Low Flow estimates from NZRiverMaps (4.9 m^3/s), the flushing time is predicted to increase to 0.6 days which is too short to sustain phytoplankton blooms. However, with the uncertainty in estuary volumes contained in Coastal Explorer, this estimate of flushing time is also uncertain, and consequently the susceptibility of the Tukituki Estuary to phytoplankton blooms in its close state cannot be readily assessed.

Pōrangahau Estuary is predicted to have high TN concentrations and moderate salinity, which with the high intertidal area indicate that the estuary has a high susceptibility to macroalgal blooms (band D). The flushing time (2.1 days) is too short to support phytoplankton blooms (band A), but should the mouth close, then the flushing time will increase, and phytoplankton growth may occur. The overall susceptibility is very high (band D) with macroalgae likely to the primary producer of concern. However, much of the Pōrangahau Estuary is riverine in character, so areas that support macroalgal growth may be limited.

Table 5-3: Chlorophyl-*a* observations from sites in the Ahuriri and Waitangi Estuaries, supplied by HBRC. Estuary bandings for chl-*a* are based on the 90th percentile of monthly observations. Minimum, mean and maximum chl-*a* concentrations are also reported for each site.

Estuary	Site Name	90th percentile chl-*a* (µg/l)	Observed banding	Minimum chl-*a* (µg/l)	Mean chl-*a* (µg/l)	Maximum chl-*a* (µg/l)
Ahuriri	Quarantine Rd	36.8	D	0.78	9.47	92
Ahuriri	Turfrey Road	40.4	D	1.25	15.85	60
Ahuriri	Watchman Road	21.6	D	0.33	6.92	210
Ahuriri	Woolshed Road	6.38	B	2.6	20.13	123
Ahuriri	Pandora Bridge	1.595	A	0.19	1.04	9.4
Waitangi	Clive River at Boat Ramp	18.32	D	0.006	5.39	26
Waitangi	Waitangi Estuary at Mouth	2.12	A	0.05	1.03	8.5

Table 5-4: Results from ETI tool 1 dilution modelling approach for assessing eutrophication susceptibility. Results for the Tukituki Estuary are for when the estuary is open to the sea (the usual state). If the Tukituki Estuary is closed for longer than 3-5 days, there may be increased susceptibility to eutrophication. Macroalgal bands for Waitangi and Tukituki estuaries are predicted to be band A based on zero salinity, but have been increased to band B due to their high nutrient concentrations and the possibly of elevated (brackish) salinity in parts of the estuaries.

Estuary	Intertidal area (%)	TN annual (mg/m^3)	TP annual (mg/m^3)	Salinity annual	Macroalgal band	TN summer (mg/m^3)	TP summer (mg/m^3)	Salinity Summer	Flushing time summer (days)	Chl-a (µg/l)	Phytoplankton band	Overall susceptibility
Maungawhio Lagoon	78.7	295	64	24	C	187	48	25	3.2	0	A	C
Wairoa River	15.6	490	238	3	*D*	367	229	12	1.1	0	A	D
Ahuriri Estuary	*9.2*	492	59	21	D	342	52	21	36	38	D	D
Waitangi Estuary	0	860	224	0	B*	408	140	5	0.99	0	A	A
Tukituki Estuary	28	1,180	209	0	B*	733	198	0	0.13	0	A	B
Pōrangahau River	81	585	149	21	D	586	187	17	2.1	0	A	D

6 Estuary Trophic Index predicted score (ETI tool 3)

6.1 Description of ETI tool 3

ETI tool 3 is a predictive tool that gives estimates of the response of both primary indicators (macroalgae and phytoplankton) and secondary indicators (sediment oxygenation as apparent redox potential discontinuity depth, sediment organic carbon, macrobenthos as NZ AMBI (Robertson et al. 2016d), proportion of natural sea grass cover and water column oxygen concentration) to nutrient loading (Zeldis and Plew in prep). ETI tool 3 is a Bayesian Belief Network (BBN), where probability tables, informed by empirical relationships obtained from international and NZ observational and model results, link nodes within the BBN. When used in a purely predictive manner, the state of driver nodes (blue in Figure 6-1) are set using information that can be obtained from running ETI tool 1. The driver nodes feed into primary indicator nodes (green) as well as intermediate calculation nodes (grey). The secondary indicator nodes (pink) are informed by driver nodes, primary indicator nodes and intermediate calculation nodes. The two primary indicator nodes are combined to obtain the primary indicator score, while the five secondary indicator nodes give the secondary indicator score (the choice of which nodes are used depends on estuary type). The primary and secondary indicator scores are averaged to give a final ETI score between 0-1, where 0 = no symptoms of eutrophication and 1 = extremely eutrophic, along with the ETI band (A to D). The scoring system in the BBN follows that used in ETI tool 2 where observations of estuary indicators are used to score an estuary's level of eutrophication (Robertson et al. 2016c). Because the BBN is probabilistic, the final ETI score includes an estimate of uncertainty.

A benefit of the ETI BBN is that it can resolve complex interactions among indicators which, in combination, form the ETI score. For example, the BBN includes sediment load as an input to predict the average estuary mud content, but the mud content does not contribute directly to the ETI score. While some ETI tool 2 assessments include the proportion of estuary area with >25% soft mud as a secondary indicator (e.g., Stevens and Rayes 2018), muddiness itself is not an expression of eutrophication, but can interact with, and worsen, other indicators of eutrophication.

Where primary or secondary indicator values are known, these can be entered into the BBN to refine and reduce the uncertainty of the ETI score. For this screening assessment, only driver node data obtained from ETI tool 1 are used as inputs to the BBN (Table 6-1). The BBN uses the presence of water column stratification to condition the water column oxygen prediction. Here, it is assumed that the Maungawhio Lagoon does not stratify because it is shallow and likely well-mixed. The Tukituki River is predicted to be a freshwater dominated system and, being shallow, is not expected to develop significant stratification. The other estuaries are assumed to be able to develop stratification, although changing this setting in the BBN does not significantly alter the final ETI scores. Wairoa Estuary is modelled as both a SSRTRE, which is appropriate for the main stem of the estuary, and a SIDE which may be more representative of the lagoon. The modelling also has Tool 1 inputs evaluating the summer freshwater flushing times of the systems (when phytoplankton and macroalgal growth rates are maximal), and seasonality factor, to convert annual potential TN loads to summer loads.

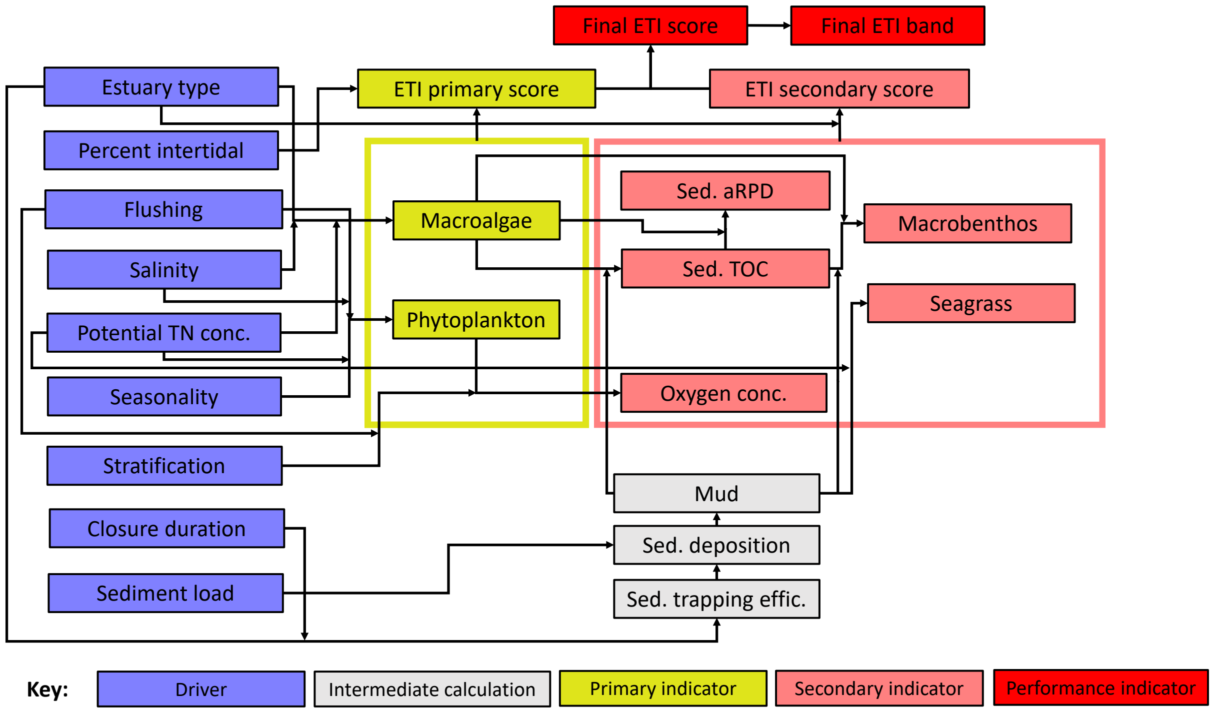

Figure 6-1: Schematic of the ETI Tool 3 Bayesian Belief Network (BBN). Information on 'drivers' (blue nodes) are derived from ETI tool 1 and input by the user, and the BBN calculates states of primary and secondary trophic indicators (green and pink 'indicator' nodes). Primary and secondary indicator values are used to produce ETI primary and secondary scores, which are then combined to give the final ETI 'performance' score and banding (red nodes).

Table 6-1: Input data for ETI tool 3. See text for heading definitions.

Estuary	Type	Intertidal area (%)	Summer flushing time (days)	Salinity	Potential TN (mg/m^3)	Seasonality	Stratification	Closure	Sediment load ($g/m^2/d$)
Maungawhio Lagoon	SIDE	79	3.2	24	295	0.633	No	Open	84
Wairoa River	SSRTRE/SIDE	16	1.1	3.2	490	0.750	Yes	Open	5130
Ahuriri Estuary	SIDE	9.2	36	21	492	0.695	Yes	Open	9.7
Waitangi Estuary	SSRTRE	0	1.0	0	860	0.485	Yes	Open	5809
Tukituki	SSRTRE	28	0.13	0	1,180	0.620	No	Open	12,276
Porangahau River	SIDE	81	2.1	21	585	0.657	Yes	Open	318

6.2 ETI tool 3 results

The BBN predicts that Waitangi Estuary and the Tukituki Estuary, with ETI scores of 0.31 ± 0.13 and 0.40 ± 0.15 respectively, are mostly likely to be placed in ETI band B (Table 6-2). As such, ecological communities are expected to be slightly impacted by the effects of additional macroalgal and/or phytoplankton growth caused by elevated nutrient levels. These estuaries are predicted to be in a healthy state. Probability distributions for the various primary and secondary indicators are shown in Figure 6-2D and E. Both estuaries are predicted to have lost significant portions of any natural seagrass cover, and to have elevated mud content, but water column oxygen is high, and the NZ AMBI scores are low (good).

Wairoa River has a predicted ETI score of 0.41 ± 0.15, also within ETI band B (Table 6-2). Ecological communities are likely to be slightly impacted by elevated macroalgal and/or phytoplankton biomass, with similar predictions for secondary indicators as described for the Waitangi and Tukituki estuaries (Figure 6-2 B). However, the lagoon to the east of the river mouth, with large intertidal extents, may be more sensitive to macroalgal growth than the main river channel. If the estuary were modelled as a SIDE, considering this intertidal lagoon, then the BBN gives a predicted score of 0.76 ± 0.18, on the threshold between bands C and D.

Maungawhio Lagoon has a predicted ETI score of 0.66 ± 0.18, which is in ETI band C (Table 6-2). At this level, ecological communities begin to be moderately impacted by elevated macroalgal and/or phytoplankton biomasses. The BBN indicates that there may be areas of increased soft mud, reduced aRPD and increased sediment carbon content (Figure 6-2 A).

Ahuriri Estuary and Pōrangahau River are both predicted to have high ETI scores of 0.82 ± 0.12 and 0.85 ± 0.11 respectively, placing both with ETI band D (Table 6-2). Ecological communities are likely to be strongly impacted by elevated macroalgal and/or phytoplankton communities. Persistent very high macroalgae cover and/or biomass may be expected, with degraded sediment quality. Flushing times are short, but under low flow conditions, may be sufficiently long that phytoplankton blooms may occur, potentially resulting in low oxygen concentrations in deep poorly flushed parts of the estuaries (Figure 6-2C and F). Both estuaries are predicted to have areas of poor sediment oxygenation (shallow aRPD), high sediment organic content, and strongly modified benthic communities.

Table 6-2: ETI scores and band predicted by ETI tool 3. The ETI score and band are calculated for Wairoa River both as a SSRTRE, which represents the main arm of the estuary, and a SIDE which may better indicate the state of the lagoon to the east of the estuary mouth.

Estuary	Predicted ETI score	Predicted ETI band
Maungawhio Lagoon	0.66 ± 0.18	C
Wairoa River (SSRTRE)	0.41 ± 0.15	B
Wairoa River (SIDE)	0.76 ± 0.18	D
Ahuriri Estuary	0.82 ± 0.12	D
Waitangi Estuary	0.31 ± 0.13	B
Tukituki Estuary	0.40 ± 0.15	B
Porangahau River	0.85 ± 0.11	D

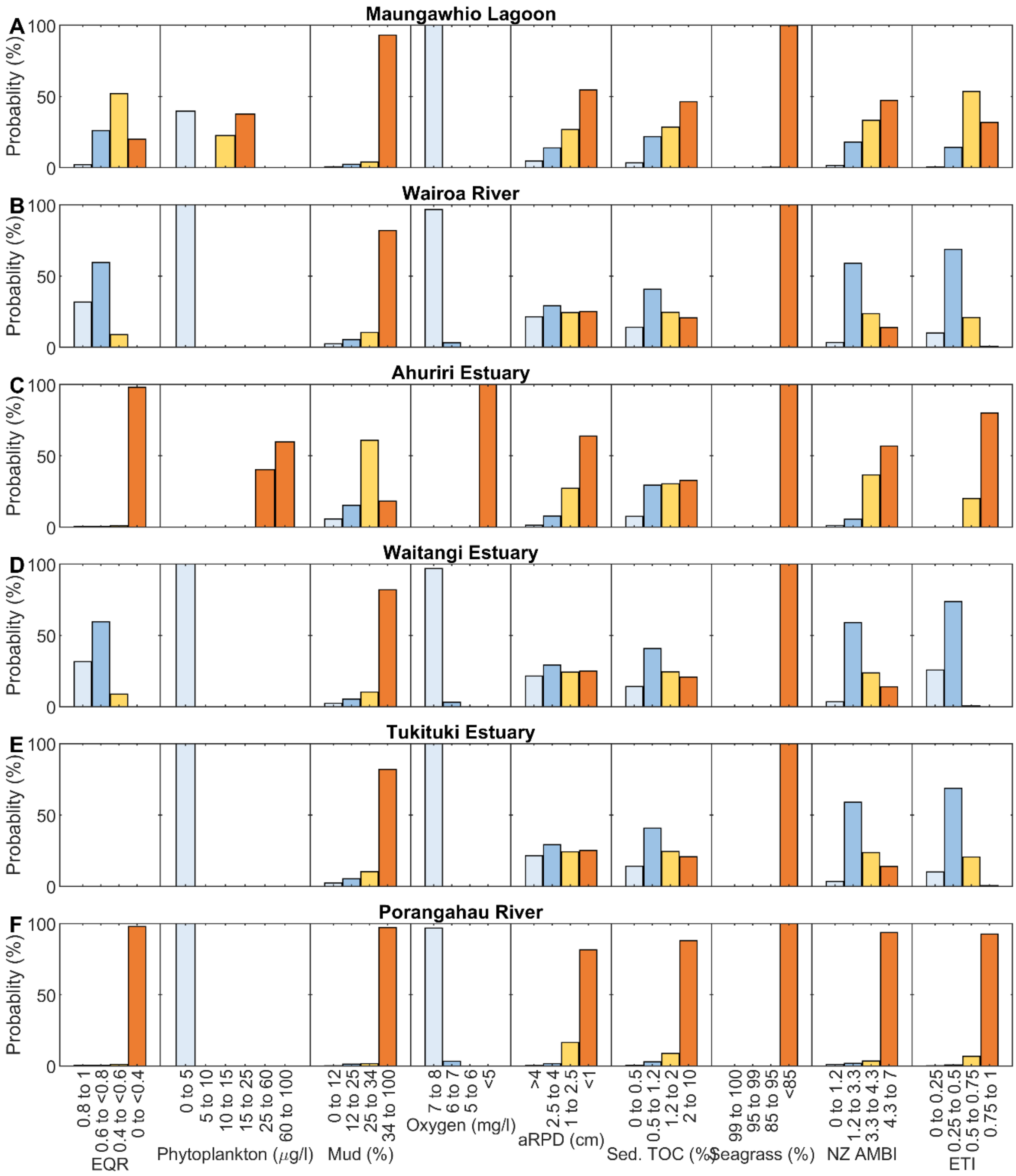

Figure 6-2: Outputs from ETI Tool 3 Bayesian Belief Network (BBN). The bar charts show the probability distributions for each primary indicator (EQR and phytoplankton), mud content, secondary indicator (water column oxygen, apparent redox potential discontinuity depth, sediment total organic carbon, proportion of natural seagrass cover remaining and macrobenthos (NZ AMBI)), and overall ETI score. Wairoa River is shown modelled as an SSRTRE.

7 Summary

7.1 Comparison of predictions

Results from the three predictions of estuary eutrophication susceptibility are summarised in Table 7-1. All three methods predict that Pōrangahau River is likely to be highly susceptible to eutrophication (band D). Whether or not eutrophic symptoms are present would need to be confirmed by field observations. While Pōrangahau River estuary has been classified as a SIDE here, much of the estuary has the characteristics of an SSRTRE, which are more resilient to elevated nutrient loads due to their short flushing times and high velocities (Robertson et al. 2016a).

The two ETI tool 1 methods (ASSETS and dilution modelling) predict that Wairoa River has a very high eutrophication susceptibility (band D), while ETI tool 3 predicts either band B or D depending on whether the estuary is classified as a SSRTRE or a SIDE. The D-band would apply to the lagoon, while the main channel is band B.

ETI tools 1 and 3 predict that Ahuriri Estuary has a very high eutrophication susceptibility (band D) while the ASSETS approach gives a slightly lower susceptibility of high (band C).

Maungawhio Lagoon is in band C (high susceptibility) according to ASSETS and ETI tool 3, and band B (moderate) according to ETI tool 1. The predicted ETI score of 0.55 is close to the B/C threshold, which suggests that there may be some expressions of eutrophication within the lagoon, but they are not expected to be widespread.

The three methods give disparate scores for Waitangi Estuary. The estuary is predicted to have a very high susceptibility (band D) according to ASSETS, a low susceptibility according to ETI tool 1 (band A), and a moderate susceptibility (band B) according to ETI tool 3. Similarly, Tukituki Estuary is predicted to have an very high susceptibility (band D) according to ASSETS, and a moderate susceptibility (band B) according to ETI tool 1 and ETI tool 3. Both estuaries are SSRTREs with high freshwater input, low salinities, low intertidal area and short flushing times. They both have very high nutrient concentrations (Table 5-4). As noted above, SSRTREs are more resilient to high nutrient loads than other estuary types (Robertson et al. 2016a), and their physical characteristics mean that eutrophic conditions are uncommon, and if present, confined to 'high risk' areas.

Table 7-1: Comparison of eutrophication susceptibilities predicted by ASSETS, dilution modelling (tool 1), and the BBN (tool 3). Tool 3 values in brackets for the Wairoa Estuary indicate results if the estuary is modelled as a SIDE, which may be appropriate for the lagoon adjacent the estuary channel.

Estuary	ETI tool 1 ASSETS susceptibility band	ETI tool 1 dilution modelling susceptibility band	ETI tool 3 BBN predicted ETI band	ETI tool 3 Predicted ETI score
Maungawhio Lagoon	C	B	C	0.66 ± 0.18
Wairoa River	D	D	B (D)	0.41 ± 0.15 (0.76 ± 0.18)
Ahuriri Estuary	C	D	D	0.82 ± 0.12
Waitangi Estuary	D	A	B	0.31 ± 0.13
Tukituki Estuary	D	B	B	0.40 ± 0.15
Pōrangahau River	D	D	D	0.85 ± 0.11

7.2 Limitations

The susceptibility assessments presented here are based on approximated estuary properties such as volume and tidal prism obtained from Coastal Explorer (which is derived from aerial photographs, maps, and charts), or directly from satellite or aerial images (Tukituki and Pōrangahau). These data can be inaccurate or outdated, affecting the susceptibility predictions. Similarly, nutrient loads and sediment loads have been obtained from models (e.g., CLUES) rather than observations. The ETI tool 1 dilution model also uses a tuning factor to account for exchange between the estuary and ocean, and this parameter was set using an empirically relationship derived from previous studies for most of the estuaries (Plew et al. 2018). Observed salinities were used to parameterise the dilution model for Ahuriri Estuary and Waitangi Estuary, but these observations were not collected in such a way to calculate a volume-averaged salinity at high tide, at a known inflow and tidal prism, in order to correctly calibrate the dilution models. The accuracy of the susceptibility assessments can be improved by:

1. Collecting bathymetry and water level data to obtain correct estuary volumes, areas, and tidal prisms.
2. Measuring nutrient loads and river flows.
3. Conducting a salinity survey, collecting salinity profiles through the estuaries at or near high tide under known inflows to calibrate the dilution model.

For some estuaries, it may be beneficial to develop multi-compartment models, or even three dimensional (3-D) numerical models, to resolve distinct parts of the estuary, for example the lagoons of Maungawhio Lagoon and Wairoa Estuary, or the separate arms of the Waitangi Estuary.

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Nutrient loads were obtained from CLUES modelling by Annette Semadeni-Davis (NIWA).

9 Glossary of abbreviations and terms

ASSETS	Assessment of Estuary Trophic Status.
DSDE	Deeper subtidal dominated, longer residence time estuaries
ETI	New Zealand Estuary Trophic Index – a set of tools for assessing the susceptibility of, and measuring the health of estuaries
Flushing time	The time (days) to replace the freshwater content within an estuary. This is calculated from freshwater inflow, estuary volume at high tide, and the dilution factor (parameterising the exchange between the estuary and ocean)
ICOE	Intermittently closed and open estuary
NZCHS	New Zealand Coastal Hydrosystem topology – a geomorphic classification of estuary types with 11 main classes.
Potential nutrient concentration	The concentration of a nutrient (TN or TP) that would occur in the estuary if nutrients were conservative tracers (i.e., no biological uptake or losses to settling or biogeochemical processes such as denitrification)
SIDE	Shallow intertidally dominated estuary
SSRTRE	Shallow, short residence time tidal river and tidal river with adjoining lagoon estuary
TN	Total nitrogen concentration (mg m^{-3})
TP	Total phosphorus concentration (mg m^{-3})

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