Wriggle coastalmanagement

NIWA Taihoro Nukurangi

NZ Estuary Trophic Index

SCREENING TOOL 1. DETERMINING EUTROPHICATION SUSCEPTIBILITY USING PHYSICAL AND NUTRIENT LOAD DATA

Prepared for

Envirolink Tools Project: Estuarine Trophic Index

MBIE/NIWA Contract No: C01X1420

December 2015

STATEMENT OF AUTHORSHIP CONTRIBUTIONS

The ETI Screening Tool 1 and 2 technical report writing was done almost exclusively by Barry Robertson and Leigh Stevens (Wriggle Coastal Management) and Ben Robertson (Wriggle/University of Otago), including literature review, typology design, susceptibility assessment, NZ specific assessment approaches, indicator selection, initial thresholds and bandings, index scoring, data compilation, and development of underpinning supporting relationships. John Zeldis (NIWA) started the ETI project, led proposal writing, ran project management, contributed technical and editorial reviews of both reports with substantive additions, and managed the external reviews. Mal Green (NIWA) and Anna Madarasz-Smith (Hawkes Bay Regional Council) were key facilitators of project development and proposal writing and provided comments on the reports. Dave Plew (NIWA) provided written comments on Tool 1 and Terry Hume (Hume Consulting Ltd) reviewed the Tool 1 typology. The following contributed to a review of the technical reports at a workshop in December 2015 - Barry Robertson, Leigh Stevens, John Zeldis, Mal Green, Dave Plew, Anna Madarasz-Smith, Richard Storey (NIWA), and Megan Oliver (Wellington Regional Council).

ACKNOWLEDGEMENTS

We are grateful for the external reviews of the ETI Screening Tool 1 and 2 technical reports by Dr Drew Lohrer and Dr Mike Townsend of NIWA. We would like to also acknowledge the following for their invaluable assistance in providing data, support and advice:

The Regional Council coastal Special Interest Group (cSIG)
Nick Ward, Environment Southland
Juliet Milne, Greater Wellington Regional Council
Rachel Ozanne, Otago Regional Council
Trevor James, Tasman District Council
Dr Hilke Giles, Waikato Regional Council
Dr Sandy Elliot, NIWA
Dr Udi Shankar, NIWA

RECOMMENDED CITATION

Robertson, B.M, Stevens, L., Robertson, B., Zeldis, J., Green, M., Madarasz-Smith, A., Plew, D., Storey, R., Hume, T., Oliver, M. 2016. NZ Estuary Trophic Index Screening Tool 1. Determining eutrophication susceptibility using physical and nutrient load data. Prepared for Envirolink Tools Project: Estuarine Trophic Index, MBIE/NIWA Contract No: C01X1420. 47p.

Cover photo: Moutere Estuary, Tasman region

Waimea Estuary, Tasman region

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by

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ABBREVIATIONS			
AA (OMBT)	Affected Area	NA	Not Assessed
AF	Assimilation Factor	NEMP	National Estuary Monitoring Protocol
AIH (OMBT)	Available Intertidal Habitat	NH3	Ammonia
AMBI	AZTI Marine Biotic Index	NH4	Ammonium
aRPD	Apparent Redox Potential Discontunity	NIWA	National Institute of Water and Atmospheric Research
ASSETS	Assessment of Estuarine Trophic Status	NLI (ASSETS)	Nutrient Load Influemce
BQI	Biological Quality Index	NNE	Nutrient Numeric Endpoints
CAP	Canonical analysis of the principal coordinates	NO2	Nitrite
CCC	Criterion Continuous Concentration	NO3	Nitrate
CE	Coastal Explorer	NOF	National Objectives Framework
chl a	Chlorophyll a	NPSFM	National Policy Statement for Freshwater Management
CICEET	Cooperative Institute for Coastal & Estuarine Environmental Technology	NSL	Natural State Sediment Load
CL (ASSETS)	Catchment N Load	NSR	Natural Sedimentation Rate
CLUES	Catchment Land Use for Environmental Sustainability Model	NSW	New South Wales
CMC	Criteria Maximum Concentration	NZ	New Zealand
cSIG	Coastal Special Interest Group	NZCHT	NZ Coastal Hydrosystems Typology
CSL	Current Sediment Load	OL (ASSETS)	Ocean N Load
CSR	Current Sedimentation Rate	OMBT (WFD)	Opportunistic Macroalgal Blooming Tool
DETR	UK Department of the Environment, Transport and the Regions	P	Phosphorus
DIN	Dissolved Inorganic Nitrogen (sum of nitrite, nitrate, and ammonia)	PMAV	Provisional maximum allowable values
DO	Dissolved Oxygen	ppt	Parts per thousand
DON	Dissolved Organic Nitrogen	RPD	Redox Potential Discontunity
DP	Dilution Potential	Rw	Water residence time
DRP	Dissolved Reactive Phosphorus	S	Sulphur
DSDE	Deeper subtidal dominated, longer residence time estuaries	SAV	Submerged Aquatic Vegetation
ECG	Ecological Condition Gradient	SF	Shape Function
ECI	Entrance Closure Index	SIDE	Shallow intertidal dominated estuaries
EF	Evacuation Factor	SR	Sedimentation Rate
ENSC	Estimated Natural Seagrass Cover	SSRTRE	Shallow, short residence time tidal river estuaries
EP	Export Potential	TBI	Traits Based Index
EQR (OMBT)	Ecological Quality Rating	TL	Tidal Lagoon
ETI	Estuary Trophic Index	TN	Total Nitrogen
EV	Estuary Volume	TOC	Total Organic Carbon
FP	Flushing Potential	TP	Total Phosphorus
FPIR	Final Primary Indicator Rating	TPR	Tidal Prism Ratio
FSIR	Final Secondary (or Supporting) Indicator Rating	TR	Tidal River
FTCR	Final Trophic Condition Rating	TRD	Tidal River + Delta
FW	Freshwater	TS	Total Sulphur
GNA	Gross Nuisance Areas	TSD	Technical Supporting Document
HAB	Harmful Algal Blooms	US	United States
ICOLL	Intermittently closed/open lakes and lagoons estuaries	USA	United States of America
ITI	Infaunal Trophic Index	USEPA	United States Environmental Protection Agency
MfE	Ministry for the Environment	WDF	Water Directive Framework
N	Nitrogen	WHO	World Health Organization
N2	Nitrogen gas	WLTG	Waituna Lagoon Technical Group
N2O	Nitrous oxide	ww	Wet Weight

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1. OVERVIEW

Managing nutrients and sediment that discharge to freshwater and estuarine environments in New Zealand (NZ), where they can cause eutrophication and sedimentation problems, has become an important national issue over the last 20 years due to ongoing intensification of agriculture, in particular dairy farming (Bidwell et al. 2009; Davies-Colley et al. 2013, Snelder et al. 2014). More than half of lowland rivers fail to meet national guidelines for total nitrogen nutrient levels and clarity, and these rivers feed directly to our estuaries. Consequently, eutrophication symptoms in estuaries, including excessive algal growth, sediment anoxia, and compromised biodiversity are becoming commonplace. Unfortunately, although nutrient enrichment threatens many NZ estuaries, guidance on how to assess the extent of eutrophication (including indexes and indicators that are useful for management) is limited. As a result, it is difficult to:

- Determine the current state of estuaries with regard to eutrophication;
- Assess the effects of the recent landuse intensification and change on estuaries;
- Gauge the consequences for estuaries of nutrient limits for freshwater (e.g. the National Policy Statement for Freshwater Management, NPSFM, 2014); and
- Set nutrient load limits to achieve estuarine objectives.

In response, regional council coastal scientists sought advice via the coastal Special Interest Group (cSIG), with funding through Envirolink Tools Grant (Contract No. C01X1420), on the development of a nationally consistent approach to the assessment of estuary eutrophication, including nutrient load thresholds. The purpose of this project, called the NZ Estuary Trophic Index (ETI) toolbox, is to assist regional councils in determining the susceptibility of an estuary to eutrophication, assess its current trophic state, and assess how changes to nutrient load limits may alter its current state. It does this by providing tools for determining estuary eco-morphological type, where an estuary sits along the ecological gradient from minimal to high eutrophication, and providing stressor-response tools (e.g. empirical relationships, nutrient models) that link the ecological expressions of eutrophication (measured using appropriate indicators) with nutrient loads (e.g. macroalgal biomass/nutrient load relationships). In terms of the regional council planning framework, the ETI provides vital supporting guidance for underpinning the ecological health component of Regional Plans by identifying relevant estuary attributes and outcomes for inclusion in plans, defining methods and indicators to measure ecosystem health attributes, and providing guidelines to assess whether or not the outcomes are being met.

1.1 SCOPE

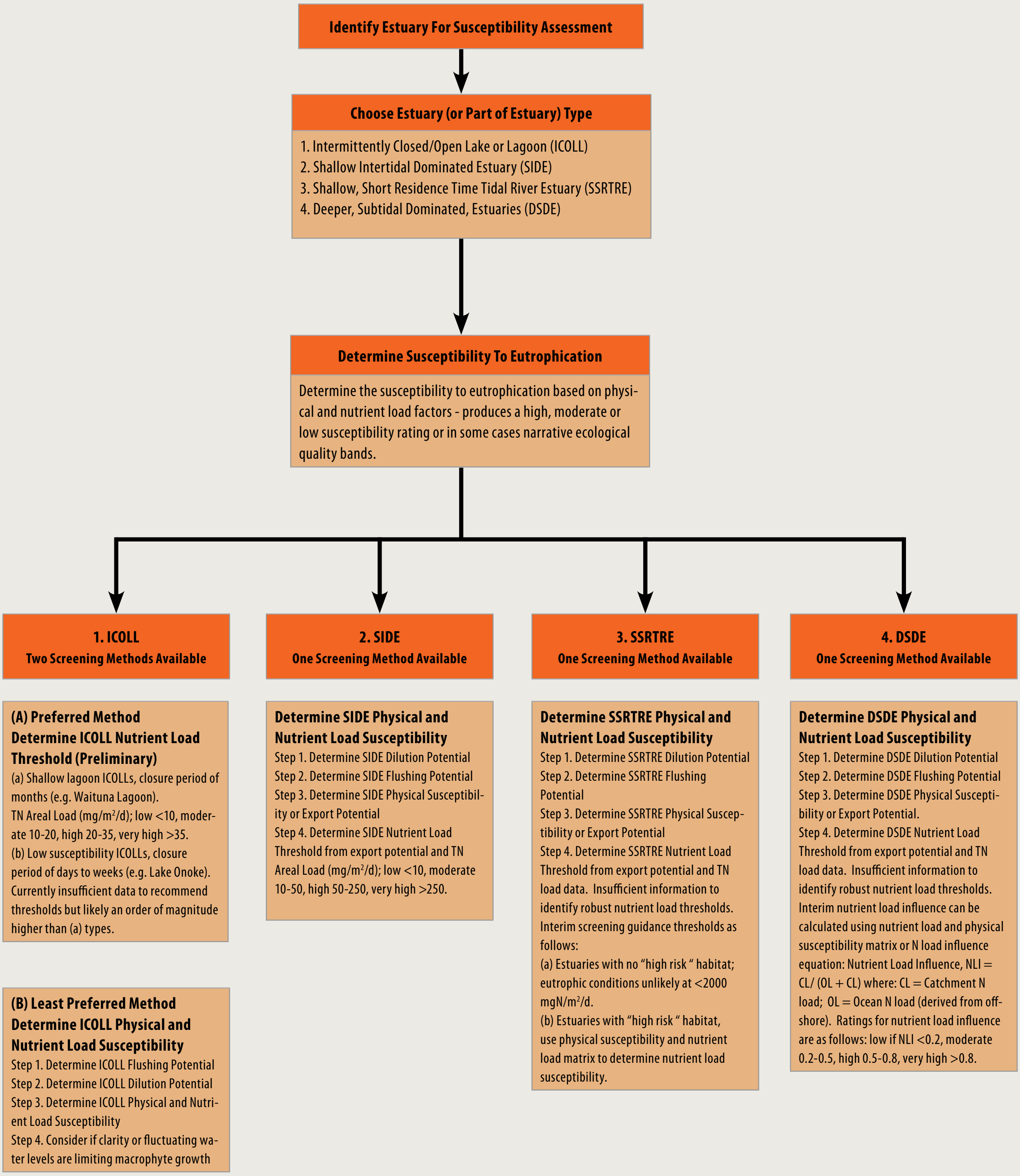
ETI Output 1 is a stand-alone, hard-copy methodology that includes two sets of tools that provide screening guidance for assessing where an estuary sits in the eutrophication gradient, and what is required to shift it to a different location in the gradient. Each tool is presented in a separate report with supporting appendices (this report presents Screening Tool 1):

- **Screening Tool 1. Physical and Nutrient Susceptibility Tool (summarised in Figure 1).**
  This method is designed to provide a relatively robust and cost effective approach to enable the prioritisation of estuaries for more rigorous monitoring and management. It applies a desktop susceptibility approach that is based on estuary physical characteristics, and nutrient input load/estuary response relationships for key NZ estuary types. The tool produces a single physical susceptibility score that can be used to classify either the ***physical susceptibility*** (i.e. very high, high, moderate, low susceptibility), and/or be combined with nutrient load data to produce a ***combined physical and nutrient load susceptibility*** rating. Nutrient areal load/trophic state bands for each estuary eutrophication type will be developed as a long term goal, with data currently available for some estuary types, but not all as yet. This section also provides guidance on the use of a simple load/response model tool provided in the ETI toolbox, and recommendations for the use of more robust approaches for setting load limits.
- **Screening Tool 2. Trophic Condition Assessment Tool (summarised in Figure 2).**
  This tool is a monitoring approach that characterises the ecological gradient of estuary trophic condition for relevant ecological response indicators (e.g. macroalgal biomass, dissolved oxygen), and provides a means of translating these ratings into an overall estuary trophic condition rating/score (the ETI). It provides guidance on which condition indicators to use for monitoring the various estuary types (and why they have been chosen), and on assessing the trophic state based on the indicator monitoring results and their comparison to numeric impairment bands (e.g. very high, high, moderate, low). The latter involves measurement of the expression of both primary (direct) eutrophication symptoms (e.g. macroalgae phytoplankton) and supporting indicators for secondary (indirect) symptoms of trophic state.

Both tools are outlined in the first section of each report and in overview flow diagrams presented in Figures 1, 2 and 3. Technical information used to support the development of the ETI, has been provided as supporting appendices referenced to each report. The appendices have been developed as a skeleton of information (including available NZ estuary data) that support the recommended ETI components for determining estuary eutrophication susceptibility and trophic condition. It is anticipated that they will be expanded upon as new information becomes available.

Screening Tool 1

For determining eutrophication susceptibility using physical and nutrient load data



Identify Estuary For Susceptibility Assessment

Choose Estuary (or Part of Estuary) Type

1. Intermittently Closed/Open Lake or Lagoon (ICOLL)
2. Shallow Intertidal Dominated Estuary (SIDE)
3. Shallow, Short Residence Time Tidal River Estuary (SSRTRE)
4. Deeper, Subtidal Dominated, Estuaries (DSDE)

Determine Susceptibility To Eutrophication

Determine the susceptibility to eutrophication based on physical and nutrient load factors - produces a high, moderate or low susceptibility rating or in some cases narrative ecological quality bands.

1. ICOLL
Two Screening Methods Available

(A) Preferred Method
Determine ICOLL Nutrient Load Threshold (Preliminary)

(a) Shallow lagoon ICOLLs, closure period of months (e.g. Waituna Lagoon).
TN Areal Load ($mg/m^2/d$); low <10, moderate 10-20, high 20-35, very high >35.
(b) Low susceptibility ICOLLs, closure period of days to weeks (e.g. Lake Onoke). Currently insufficient data to recommend thresholds but likely an order of magnitude higher than (a) types.

(B) Least Preferred Method
Determine ICOLL Physical and Nutrient Load Susceptibility

Step 1. Determine ICOLL Flushing Potential
Step 2. Determine ICOLL Dilution Potential
Step 3. Determine ICOLL Physical and Nutrient Load Susceptibility
Step 4. Consider if clarity or fluctuating water levels are limiting macrophyte growth

2. SIDE
One Screening Method Available

Determine SIDE Physical and Nutrient Load Susceptibility

Step 1. Determine SIDE Dilution Potential
Step 2. Determine SIDE Flushing Potential
Step 3. Determine SIDE Physical Susceptibility or Export Potential
Step 4. Determine SIDE Nutrient Load Threshold from export potential and TN Areal Load ($mg/m^2/d$); low <10, moderate 10-50, high 50-250, very high >250.

3. SSRTRE
One Screening Method Available

Determine SSRTRE Physical and Nutrient Load Susceptibility

Step 1. Determine SSRTRE Dilution Potential
Step 2. Determine SSRTRE Flushing Potential
Step 3. Determine SSRTRE Physical Susceptibility or Export Potential
Step 4. Determine SSRTRE Nutrient Load Threshold from export potential and TN load data. Insufficient information to identify robust nutrient load thresholds. Interim screening guidance thresholds as follows:
(a) Estuaries with no "high risk" habitat; eutrophic conditions unlikely at <2000 $mgN/m^2/d$.
(b) Estuaries with "high risk" habitat, use physical susceptibility and nutrient load matrix to determine nutrient load susceptibility.

4. DSDE
One Screening Method Available

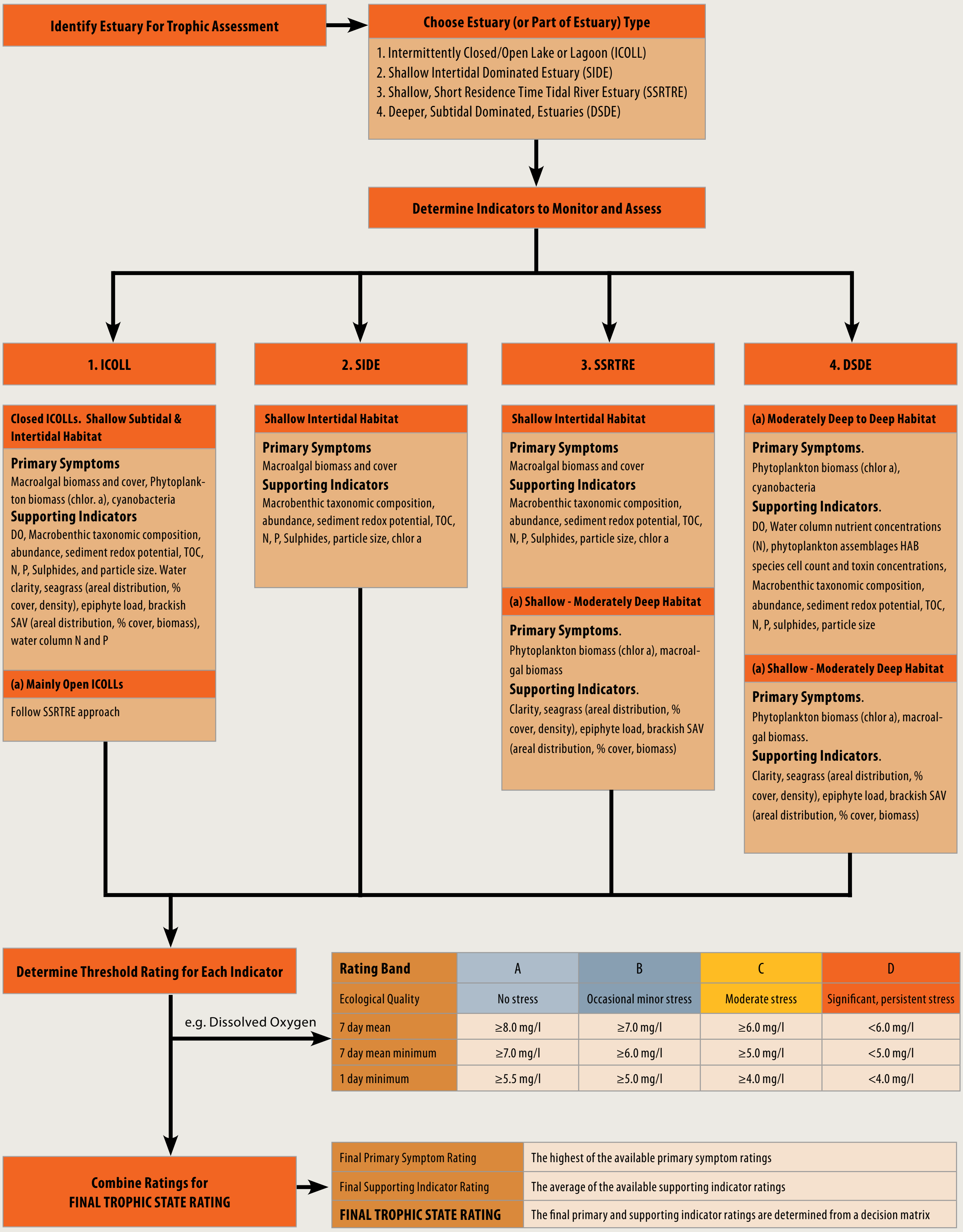
Determine DSDE Physical and Nutrient Load Susceptibility

Step 1. Determine DSDE Dilution Potential
Step 2. Determine DSDE Flushing Potential
Step 3. Determine DSDE Physical Susceptibility or Export Potential.
Step 4. Determine DSDE Nutrient Load Threshold from export potential and TN load data. Insufficient information to identify robust nutrient load thresholds. Interim nutrient load influence can be calculated using nutrient load and physical susceptibility matrix or N load influence equation: Nutrient Load Influence, NLI = CL/ (OL + CL) where: CL = Catchment N load; OL = Ocean N load (derived from offshore). Ratings for nutrient load influence are as follows: low if NLI <0.2, moderate 0.2-0.5, high 0.5-0.8, very high >0.8.

Figure 1. Screening Tool 1 - outline flow diagram.

Screening Tool 2

For determining trophic state using estuary monitoring data



Identify Estuary For Trophic Assessment

Choose Estuary (or Part of Estuary) Type

1. Intermittently Closed/Open Lake or Lagoon (ICOLL)
2. Shallow Intertidal Dominated Estuary (SIDE)
3. Shallow, Short Residence Time Tidal River Estuary (SSRTRE)
4. Deeper, Subtidal Dominated, Estuaries (DSDE)

Determine Indicators to Monitor and Assess

1. ICOLL

Closed ICOLLs. Shallow Subtidal & Intertidal Habitat

Primary Symptoms
Macroalgal biomass and cover, Phytoplankton biomass (chlor. a), cyanobacteria
Supporting Indicators
DO, Macrobenthic taxonomic composition, abundance, sediment redox potential, TOC, N, P, Sulphides, and particle size. Water clarity, seagrass (areal distribution, % cover, density), epiphyte load, brackish SAV (areal distribution, % cover, biomass), water column N and P

(a) Mainly Open ICOLLs

Follow SSRTRE approach

2. SIDE

Shallow Intertidal Habitat

Primary Symptoms
Macroalgal biomass and cover
Supporting Indicators
Macrobenthic taxonomic composition, abundance, sediment redox potential, TOC, N, P, Sulphides, particle size, chlor a

3. SSRTRE

Shallow Intertidal Habitat

Primary Symptoms
Macroalgal biomass and cover
Supporting Indicators
Macrobenthic taxonomic composition, abundance, sediment redox potential, TOC, N, P, Sulphides, particle size, chlor a

(a) Shallow - Moderately Deep Habitat

Primary Symptoms.
Phytoplankton biomass (chlor a), macroalgal biomass
Supporting Indicators.
Clarity, seagrass (areal distribution, % cover, density), epiphyte load, brackish SAV (areal distribution, % cover, biomass)

4. DSDE

(a) Moderately Deep to Deep Habitat

Primary Symptoms.
Phytoplankton biomass (chlor a), cyanobacteria
Supporting Indicators.
DO, Water column nutrient concentrations (N), phytoplankton assemblages HAB species cell count and toxin concentrations, Macrobenthic taxonomic composition, abundance, sediment redox potential, TOC, N, P, sulphides, particle size

(a) Shallow - Moderately Deep Habitat

Primary Symptoms.
Phytoplankton biomass (chlor a), macroalgal biomass.
Supporting Indicators.
Clarity, seagrass (areal distribution, % cover, density), epiphyte load, brackish SAV (areal distribution, % cover, biomass)

Determine Threshold Rating for Each Indicator

e.g. Dissolved Oxygen

Rating Band	A	B	C	D
Ecological Quality	No stress	Occasional minor stress	Moderate stress	Significant, persistent stress
7 day mean	≥8.0 mg/l	≥7.0 mg/l	≥6.0 mg/l	<6.0 mg/l
7 day mean minimum	≥7.0 mg/l	≥6.0 mg/l	≥5.0 mg/l	<5.0 mg/l
1 day minimum	≥5.5 mg/l	≥5.0 mg/l	≥4.0 mg/l	<4.0 mg/l

Combine Ratings for FINAL TROPHIC STATE RATING

Final Primary Symptom Rating	The highest of the available primary symptom ratings
Final Supporting Indicator Rating	The average of the available supporting indicator ratings
FINAL TROPHIC STATE RATING	The final primary and supporting indicator ratings are determined from a decision matrix

Figure 2. Screening Tool 2 - outline flow diagram.

SCOPE (CONTINUED)

Output 2 of the ETI will package the whole approach within a simple calculator framework to streamline the screening process, improve user-accessibility, and to provide preliminary guidance on load limits. Like the ASSETS approach, the calculator is primarily intended as a tool to estimate trophic state consistently across estuaries to set monitoring priorities. In addition, the calculator will enable the prediction of ETI bands (see Table 1) for each estuary typology under specified catchment nutrient loads, and from this, the ETI bands that supporting indicators are likely to be within. Subsequent monitoring of primary symptoms and supporting indicators is then recommended to determine actual trophic condition and to derive an ETI score. It is emphasised that the estuary response to changes in catchment nutrient loads will be strongly influenced by internal loading from sediment bound nutrients, and this may continue to drive eutrophic expressions for a considerable period after any catchment load changes (particularly reductions) are made.

This ETI combination package of ecological response indicators, thresholds, and nutrient loads, tailored for estuary type, provides a more direct risk-based linkage to estuary ecological values than nutrient concentrations or loads alone. Its weight of evidence approach, with multiple ecological response indicators and indicator thresholds and load/response relationships developed from relevant estuary ecological gradients, is expected to produce a robust assessment of eutrophication for most NZ estuary types, and to provide preliminary, screening-level, load limit guidance. For setting final load limits, the ETI recommends the use of more robust approaches; preferably relevant measured nutrient load/ecological response gradients, but if unavailable, using the modelling approaches it describes.

The approach adopted in the ETI has been to use, where appropriate, overseas estuary eutrophication assessment approaches where they meet the NZ situation {e.g. the US ASSETS framework (Bricker et al. 1999, 2003, 2007), the NSW ICOLLs approach (Haines et al. 2006) and ASSETS/DIPSIR Approach used on Basque Estuaries (Borja et al. 2006)}. Background information on these approaches is presented in Tool 1 Appendix 1. However, because the majority of NZ estuaries fall outside of the types used to develop the overseas assessment procedures, the overseas approaches have in many cases been modified to better suit the physical characteristics of NZ estuaries.

1.2. DEFINITION OF THE ESTUARINE SYSTEM

The Estuarine System used in the ETI is best understood in the context of a whole coastal and marine ecological classification approach (e.g. that adopted by Madden et al. 2009). In this approach, estuaries are one system in a total of five. Systems are differentiated from one another by a combination of salinity, geomorphology and depth. Salinity is first used to separate the truly marine systems from those influenced by freshwater. Three systems, ***Nearshore***, ***Neritic*** and ***Oceanic***, are truly marine, all having salinities greater than 30ppt throughout the year. They are distinguished from each other by depth and relative distance from the continental shelf. The remaining two systems, ***Estuarine***, and ***Freshwater Influenced***, are at least occasionally diluted (<30ppt) by significant freshwater input during the year, and are distinguished from each other by their degree of enclosure by land - Estuarine Systems are classified as having a <150 degree angle between the head of the estuary/embayment and the two outer headlands. While at least partially enclosed by land, access to the ocean can be open, partly obstructed, or sporadic, and salinity may be periodically increased above that of the open ocean by evaporation. Intermittently closed/open estuaries do not need to have a surface water tidal connection to be considered an estuary (Sutula et al. 2014). The Estuarine System extends upstream and landward, including tidal habitats and adjacent tidal wetlands.

The defined boundaries of estuaries in this report are seaward from an imaginary line closing the mouth, to landward where ocean derived salts measure less than 0.5ppt during the period of average annual low flow.

There are a large number of frameworks for describing different estuary types (typologies) and NZ estuaries have been characterised within a relatively complex typology of twelve main types (and multiple (>12) subtypes) based on broad physical (geomorphic) features (NZ Coastal Hydrosystems Typology (NZCHT) - Hume et al. 2007, Hume 2015).

Because susceptibility to eutrophication spans multiple geomorphic categories, applying a geomorphic typology becomes unnecessarily complex when assessing the susceptibility of estuaries to eutrophication which are more directly influenced by specific physical modifying characteristics including dilution, flushing, residence time, depth and intertidal extent. Therefore the ETI has adopted a simple 4 category typology specifically suited to the assessment of estuarine eutrophication susceptibility in NZ as follows:

1. Intermittently closed/open lakes and lagoons estuaries (ICOLLs)
2. Shallow intertidal dominated estuaries (SIDEs)
3. Shallow, short residence time tidal river and tidal river with adjoining lagoon estuaries (SSRTREs)
4. Deeper subtidal dominated, longer residence time estuaries (DSDEs)

These broad estuary types are described further in Table 2, and use waterbody boundaries consistent with those in the NZCHT (Hume 2015).

1.3 EUTROPHICATION PROCESS

Eutrophication of estuaries is a process driven by the enrichment of water by nutrients, especially compounds of nitrogen and/or phosphorus from land, atmosphere, or adjacent seas, and which leads to: increased growth, primary production and biomass of algae, changes in the balance of organisms, and water quality degradation. The response to nutrients is often exacerbated by the presence of muds [lower pore water exchange, increased sediment bound nutrients] and hydrological changes, including artificial opening/closing of intermittently closed/open lakes and lagoons [primarily reduced dilution and flushing]. The consequences of eutrophication are considered undesirable if they appreciably degrade ecosystem health and/or the sustainable provision of goods and services (Ferriera et al. 2011).

As an estuary, or part of an estuary, shifts along the gradient of eutrophication from "minimally eutrophic" (totally or nearly totally undisturbed conditions) to "very highly eutrophic" (highly degraded), the types and relative abundance of the primary producer communities change. These changes also vary depending on whether the estuary is shallow or deep. At the "minimally eutrophic" end of the gradient, low nutrient tolerant primary producers dominate (e.g. benthic microalgae and seagrasses in shallow estuaries, and a diverse but low biomass phytoplankton community in deep or turbid estuaries). In the "moderately eutrophic" range (i.e. moderate nutrient availability), opportunistic macroalgae and epiphytic algae dominate in shallow estuaries, while in deep or turbid estuaries, phytoplankton (including harmful species at times) are favoured (Valiela et al. 1997, Viaroli et al. 2008). At the "very highly eutrophic" end of the gradient, opportunistic macroalgae and cyanobacterial mats dominate in shallow estuaries (intertidal and subtidal habitats), and rampant algal blooms (e.g. cyanobacteria and/or pico-plankton blooms) in deeper subtidal or turbid estuaries (e.g. Cloern 2001, Boynton et al. 1996).

This increase in the rate of algal organic matter production (fuelled by excessive nutrients), and its subsequent microbial decomposition, are at the heart of the eutrophication problem. The larger the organic content, the greater the growth of microorganisms that can contribute to the depletion of oxygen supplies in sediments and deeper bottom water, causing the communities to become increasingly heterotrophic, i.e. net oxygen-consuming (Caffrey 2004; Borum and Sand-Jensen 1996). This results in elevated sediment nutrient release to the water column, thereby accelerating eutrophication and increased sulphide concentrations which have an inhibitory effect on macrophytes, macrofauna, and on some biogeochemical processes such as coupled nitrification/denitrification (Pearson and Rosenberg 1978, Kemp et al. 1990, Boynton and Kemp 2008, Hughes et al. 2011, Sutula 2011, Green et al. 2014, McGlathery 2008, Lamers et al. 2013).

A generalised summary of narrative ecological thresholds that exist along the eutrophication gradient for estuaries is shown in Table 1. These have been placed into Bands A-D, consistent with the banding approach adopted by the National Objectives Framework (NOF) to support and guide the setting of freshwater/estuary objectives in regional plans.

Table 1. A generalised summary of narrative ecological thresholds that exist along the eutrophication gradient.

Nutrient Load

→

A Minimal Eutrophication	B Moderate Eutrophication	C High Eutrophication	D Very High Eutrophication
Ecological communities are healthy and resilient. *Primary Producers: dominated by seagrasses and microalgae. **Primary Producers: dominated by phytoplankton (diverse, low biomass). Water Column: high clarity, well-oxygenated. Sediment: well oxygenated, low organic matter, low sulphides and ammonia, diverse macrofaunal community with low abundance of enrichment tolerant species.	Ecological communities are slightly impacted by additional algal growth arising from nutrient levels that are elevated. *Primary Producers: seagrass/microalgae still present but increasing biomass opportunistic macroalgae. **Primary Producers: dominated by phytoplankton (moderate diversity and biomass). Water Column: moderate clarity, mod-poor DO esp at depth. Sediment: moderate oxygenation, organic matter, and sulphides, diverse macrofaunal community with increasing abundance of enrichment tolerant species.	*Ecological communities are highly impacted by macroalgal or phytoplankton biomass elevated well above natural conditions. Reduced water clarity likely to affect habitat available for native macrophytes. **Ecological communities are highly impacted by phytoplankton biomass elevated well above natural conditions. Reduced water clarity may affect deep seagrass beds. *Primary Producers: opportunistic macroalgal biomass high, seagrass cover low. Increasing phytoplankton where residence time long e.g. ICOLLs. **Primary Producers: dominated by phytoplankton (low diversity and high biomass). Water Column: low-moderate clarity, low DO, esp at depth. Sediment: poor oxygenation, high organic matter, and sulphides, macrofauna dominated by high abundance of enrichment tolerant species.	*Excessive algal growth making ecological communities at high risk of undergoing a regime shift to a persistent, degraded state without macrophyte/seagrass cover. **Excessive algal growth making ecological communities at high risk of undergoing a regime shift to a nuisance algal bloom situation (often toxic). *Primary Producers: opportunistic macroalgal biomass very high or high/low cycles in response to toxicity, no seagrass. At very high nutrient loads, cyanobacterial mats may be present. Phytoplankton only high where residence time is long. **Primary Producers: dominated by nuisance phytoplankton (e.g cyanobacteria, picoplankton). Water Column: low clarity, deoxygenated at depth. Sediment: anoxic, very high organic matter, and sulphides, subsurface macrofauna very limited or absent. Eventually the sediments are devoid of macrofauna and are covered in mats of sulfur-oxidizing bacteria (i.e. *Beggiatoa*).

* shallow estuaries, often intertidal dominated, including shallow ICOLLs
** Open, moderate to deep subtidal dominated estuaries

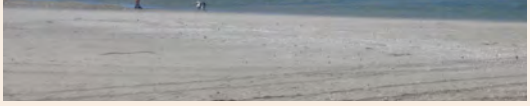
Screening Tool 1.

FOR DETERMINING EUTROPHICATION SUSCEPTIBILITY USING PHYSICAL AND NUTRIENT LOAD DATA

New River Estuary: saltmarsh in upper estuary

Jacobs River Estuary: anoxic muds in upper estuary

Moutere Inlet: anoxic muds in upper estuary



Motupipi Estuary: clean waters near mouth

2. SCREENING TOOL 1.

FOR DETERMINING EUTROPHICATION SUSCEPTIBILITY USING PHYSICAL AND NUTRIENT LOAD DATA

2.1. SUSCEPTIBILITY METHODS AND SUPPORTING INFORMATION

The eutrophication susceptibility of estuaries to increased nutrient loads varies depending on certain physical factors (morphometric and hydrological) that determine how an estuary dilutes and retains inflowing nutrients that are not flushed to sea or lost to the atmosphere through denitrification. The input/dilution/retention/exit process for nutrients is relatively simple. The nutrient load enters the estuary, it is diluted within it, some of the diluted load is retained (primarily through such processes as plant uptake and sedimentation), and the remainder exits to the sea or atmosphere. Eutrophication occurs if the load is excessive, dilution is minimal, and retention is encouraged. Because the potential for dilution and retention varies with an estuary's biogeochemical characteristics as well as the nutrient load, these characteristics (i.e. nutrient load and physical characteristics) both need to be incorporated in predictions of susceptibility to eutrophication.

In general, the approach taken by the ETI to provide guidance on the susceptibility of NZ estuary types to eutrophication is to use a combination of:

- a typological system for classifying estuaries,
- existing physical susceptibility indicators (e.g. as provided in US based ASSETS and New South Wales (NSW) ICOLLs approaches),
- additional physical indicators to account for shallow estuary types in NZ,
- nutrient loads and, to a lesser extent, concentrations (Appendix 2 provides technical supporting information for developing nutrient load/estuary response relationships).

Detailed summaries of the ASSETS and the NSW ICOLLs approaches to identifying physical susceptibility to eutrophication, and recommended modifications for their use on NZ estuaries, are presented in Appendix 1.

The following subsections provide the methodologies, and directions for accessing the supporting information, for assessing physical and nutrient load (or nutrient concentration) susceptibility of each of four NZ estuary categories (Table 2).

A summary flow diagram of the susceptibility process is provided in Figure 1.

Lake Brunton: ICOLL in Southland

Haldane Estuary: Southland

Havelock Estuary: at head of Pelorus Sound

Wanganui Estuary: tidal river estuary

Table 2. Main Estuary Categories used in Eutrophication Susceptibility Analysis

1. Intermittently Closed/Open Lake and Lagoon Estuaries (ICOLLs)

Shallow tidal lagoon and tidal river type estuaries (<3m deep) that experience periodical mouth closure or constriction (called ICOLLs) have the highest susceptibility to nutrient retention and eutrophication, with the most susceptible being those with closure periods of months (e.g. Waituna Lagoon) rather than days (e.g. Lake Onoke). In general, the tidal river ICOLLs have shorter periods of mouth closure (unless they are very small) than the more buffered tidal lagoon ICOLLs. The high susceptibility arises from reduced dilution (absence of tidal exchange at times) and increased retention (through both enhanced plant uptake and sediment deposition). Excessive phytoplankton and macroalgal growths and reduced macrophyte growth are characteristic symptoms of ICOLL eutrophication. In ICOLLs, which vary between marine and close to freshwater salinities, a co-limiting situation between N and P is expected, and as a consequence nutrient load/estuary response relationships should consider both N and P.
Susceptibility to Nutrient Loads: Very High
Major Primary Producers: Both Macroalgae and Phytoplankton

Waituna Lagoon (Southland): high susceptibility ICOLL

2. Shallow, Intertidal Dominated Estuaries (SIDEs)

For NZ's dominant estuary types (i.e. shallow, short residence time (<3 days), and predominantly intertidal, tidal lagoon estuaries and parts of other estuary types where extensive tidal flats exist e.g. Firth of Thames, Kaipara Harbour, Freshwater Estuary), flushing is too strong for significant retention of dissolved nutrients. Nevertheless, retention can still be sufficient to allow for retention of fine sediment and nutrients (particularly if these are excessive), deleterious for healthy growths of seagrass and saltmarsh, and nuisance growths of macroalgae in at-risk habitat. In these latter estuary types, assessment of the susceptibility to eutrophication must focus on the quantification of at-risk habitat (generally upper estuary tidal flats), based on the assumption that the risk of eutrophication symptoms increases as the habitat that is vulnerable to eutrophication symptoms expands. Nitrogen has been identified as the element most limiting to algal production in most estuaries in the temperate zone and is therefore the preferred target for eutrophication management in these estuaries (Howarth and Marino 2006).
Susceptibility to Nutrient Loads: Moderate to High
Major Primary Producers: Macroalgae

Freshwater Estuary (Stewart Island): high susceptibility pristine estuary

3. Shallow, Short Residence Time Tidal River, and Tidal River with Adjoining Lagoon, Estuaries (SSRTREs)

NZ also has a number of shallow, short residence time (<3 days) tidal river estuaries (including those that exit via a very well-flushed small lagoon) that have such a large flushing potential (freshwater inflow/estuary volume ratio >0.16) that the majority of fine sediment and nutrients are exported to the sea. Tidal River ICOLLs with closure periods of days rather than months and high freshwater inflows (e.g. Lake Onoke) can also fit in this category. In general, these estuary types have extremely low susceptibilities and can often tolerate nutrient loads an order of magnitude greater than shallow, intertidal dominated estuaries. These shallow estuary types are generally N limited.
Susceptibility to Nutrient Loads: Low to Very Low
Major Primary Producers: Macroalgae, but low production, especially if freshwater inflow high.

Waimatuku Estuary (Southland)

4. Deeper, Subtidal Dominated, Estuaries (DSDEs)

Mainly subtidal, moderately deep (>3m to 15m mean depth) coastal embayments (e.g. Firth of Thames) and tidal lagoon estuaries (e.g. Otago Harbour), with moderate residence times >7 to 60 days) can exhibit both sustained phytoplankton blooms, and nuisance growths of opportunistic macroalgae (especially *Ulva* sp. and *Gracilaria* sp.) if nutrient loads are excessive. The latter are usually evident particularly on muddy intertidal flats near river mouths and in the water column where water clarity allows. Deeper, long residence time embayments and fiords are primarily phytoplankton dominated if nutrient loads are excessive. Outer reaches of such systems which sustain vertical density stratification can be susceptible to oxygen depletion and low pH effects (Sunda and Cai 2012, Zeldis et al. 2015). In both cases, it is expected that the US ASSETS approach will adequately predict their trophic state susceptibility. These deeper estuary types are generally N limited.
Susceptibility to Nutrient Loads: Moderate to Low
Major Primary Producers: Macroalgae (moderately deep) and phytoplankton (deeper sections).

Pelorus Sound (Marlborough)

STEP 1. DETERMINE CATEGORY OF ESTUARY (OR PART OF ESTUARY)

The four broad estuary categories identified in the ETI in terms of their response to eutrophication are:

1. Intermittently closed/open lake and lagoon estuaries (ICOLLs)
2. Shallow intertidal dominated estuaries (SIDEs)
3. Shallow, short residence time tidal river and tidal river with adjoining lagoon estuaries (SSRTREs)
4. Deeper subtidal dominated, longer residence time, estuaries (DSDEs)

The first step is to choose which category the chosen estuary (or part of an estuary) falls into, noting that many estuaries have habitats within them that fit within other estuary categories. For example, the Firth of Thames fits primarily the DSDE category in deeper main basin areas, but also has extensive shallow intertidal flats and tidal rivers that are best assessed using approaches for SIDEs or SSRTREs. The ETI allows for this overlap by encouraging the user to apply the tools on a dominant habitat basis (e.g. for the Firth of Thames, the user may apply the protocol for category 2 estuaries to the intertidal flats and the category 4 protocol for deeper main basin area.

A simple summary table is presented below to guide initial category selection for either the whole estuary, or the subcomponent of an estuary that is being assessed.

Broad Estuary Category				
Key Features	Estuarine System = Mean salinity >0.5 and <30ppt during average annual low flow, <150° angle between head of estuary and two outer headlands			
	ICOLL	**SIDE**	**SSRTRE**	**DSDE**
	Lagoon or Tidal River shape	Lagoon shape	Tidal River shape	Generally long residence (<7 days)
	Shallow (<3m deep)	Shallow (<3m deep)	Shallow (<3m deep)	Deep (>3m deep)
	Mouth opens and closes	>40% of estuary is intertidal	High Flushing Potential (e.g. FP>0.16)	
	Variable residence time	Generally short residence (<3 days)	Generally short residence (<3 days)	

Once the estuary category is selected, the second step is to determine susceptibility to eutrophication based on the relevant tools presented in the following sections.

STEP 2. DETERMINE SUSCEPTIBILITY TO EUTROPHICATION

USING PHYSICAL AND NUTRIENT LOAD DATA

1. ICOLL SUSCEPTIBILITY

Intermittently closed/open lake and lagoon estuaries

In ICOLLs, eutrophication involves regime shifts as nutrient loads and concentrations increase e.g. pristine seagrass communities (e.g. *Ruppia* spp.) succumb to macroalgae and epiphytes, which succumb to phytoplankton such as cyanobacteria (Viaroli et al. 2008). Although they can co-exist in a relatively balanced state, specific nutrient loading rates tend to favour one of these groups. In some instances, the relationships tend to be linear (e.g. Boynton et al. 1996, Fox et al. 2008), but in others they appear to be non-linear, with clear thresholds (e.g. Burkholder et al. 2007, Sanderson and Coade 2010), suggesting rapid shifts in communities as loading rates increase through the threshold values. The shapes of these relationships undoubtedly have to do with the lengths of the trophic gradients examined and with the strengths of the negative and positive ecological feedbacks specific to each system (Scheffer and van Nes 2004). Loading rates which delineate transitions from one group to another along a nutrient enrichment gradient have been referred to as nutrient loading thresholds.

In NZ, ICOLLs tend to be shallow (<3m mean depth) and, because they experience periodical mouth closure or constriction, they have an increased susceptibility to nutrient retention and eutrophication, with the most susceptible being those with closure periods of months (e.g. Waituna Lagoon) rather than days (e.g. Lake Onoke). In general, the tidal river ICOLLs have shorter periods of mouth closure than the more buffered tidal lagoon ICOLLs. A common symptom of eutrophication in NZ shallow, occasionally “open”, brackish ICOLLs (e.g. Waituna Lagoon) is the presence of epiphyte “slime” on *Ruppia* leaves and on the sediments which causes high sulfide production. Such conditions are common in overseas ICOLLs [e.g. a brackish lagoon in France (Viaroli et al. 1996), where it has been suggested that excessive loads of epiphytes and macroalgae contribute to sulfide toxicity and destabilisation of the macrophyte communities (Burkholder et al. 1994)].

The recommended steps for determining the physical and nutrient load susceptibility of ICOLLs and the supporting information follow below: It is noted that the thresholds are based on limited data and therefore should be used for preliminary monitoring and “screening-type” management guidance, and supported by more detailed site-specific studies for final nutrient load assessments. The following two screening methods are provided for determining susceptibility to nutrient loads based on physical factors:

ICOLL: SUSCEPTIBILITY (CONTINUED)

(A) PREFERRED ICOLL SUSCEPTIBILITY SCREENING METHOD.

The first method (based on NZ ICOLL nutrient load data and trophic response data/expert information) is for two ICOLL susceptibility categories - High Susceptibility ICOLLs [shallow (<3m mean depth), tidal lagoon ICOLLs with closure periods of months rather than days], or Low Susceptibility ICOLLs [which have closure periods of days rather than months (e.g. Lake Onoke)]. It requires input of annual nutrient load and type of ICOLL, with the output being identification of the likely ecological quality band (including narrative description) for that load.

(i) High Susceptibility ICOLLs.

For shallow (<3m mean depth) tidal lagoon ICOLLs with closure periods of months rather than days the following guideline nutrient loading thresholds are recommended (TN concentrations indicative of degraded conditions are presented in Appendix 3):

Band	A	B	C	D
Total Nitrogen Load* (mg/m^2/d) based on mean annual estimates	<10	10-20	>20-35	>35
Total Phosphorus Load* (mg/m^2/d) based on mean annual estimates	<0.5	0.5-1.5	>1.5-5.5	>5.5
Ecological Quality	No stress caused by the indicator on any aquatic biota. Healthy seagrass communities present.	A minor stress on sensitive biota caused by the indicator. Some eutrophic symptoms (e.g. macroalgae) but still support healthy seagrass and fish communities.	Moderate stress on a number of aquatic biota caused by the indicator exceeding preference levels for some species and a risk of sensitive biota species being lost or reduced. Macroalgal growth moderate.	Significant, persistent stress on a range of aquatic biota caused by the indicator exceeding tolerance levels. A likelihood of local extinctions of keystone species and loss of ecological integrity. Algal dominated, turbid systems, seagrass absent or reduced.

* In ICOLLs, the management for both N and P is particularly important because of their characteristic switching between freshwater and brackish conditions (Schallenberg and Schallenberg 2012). To estimate the nutrient load, model estimates of catchment nutrient loads (supplemented with point source input data) are the logical first source of these data (e.g. NIWA's CLUES Model, SCENY Model - Heggie and Savage (2009), etc.) bearing in mind that model data will likely need to be validated, or at least exposed to sensitivity analysis, once major management decisions are being addressed. Once the load is estimated in kgN/yr or kgP/yr, then normalise it to the estuary area (i.e. mgN.m^2.yr^{-1}) by the following equation: Areal N load (mgN.m^2.yr^{-1}) = N load (kg/yr)/Area Estuary (km^2)

* * Median to apply both during periods when the ICOLL is open and during periods when the ICOLL is closed. Based on a rolling median of at least 12 samples for each situation (i.e. open or closed), and assuming a regular (e.g. monthly) monitoring regime.

(ii) Low Susceptibility ICOLLs.

Currently, there are insufficient data to recommend thresholds for ICOLLs with closure periods of days rather than months (e.g. Lake Onoke), but what is available indicates the nutrient load thresholds are likely to be greater than an order of magnitude higher than for the high susceptibility ICOLLs.

(B) LEAST PREFERRED ICOLL SUSCEPTIBILITY SCREENING METHOD.

The second method (modified New South Wales ICOLLs approach), involves input of annual nutrient load and physical factors. The output is a susceptibility rating of low, moderate, high, or very high. This method has limitations, particularly the fact that the NSW classifications lack the validation of susceptibility/trophic response relationships and therefore provide only a relative classification of overall susceptibility. Clearly, the classifications would be more useful in the NZ context if trophic status data were used to help choose appropriate classification boundaries. The approach is as follows and involves three steps.

Step 1. Determine ICOLL Flushing Potential (ICOLL FP)	**ICOLL FP =** $ECI_{consec} \div (FW/EV)$. Where ECI_{consec} is the the longest proportion of time that the entrance of an ICOLL is closed over consecutive days and is calculated over a long-term period. FW is the freshwater inflow in m^{3}yr^{-1}. EV is estuary volume (m^3) when closed. For unstratified ICOLLs: If answer = >100 then rating is Very High; 10-100 then rating is High; 1-10 then rating is Moderate; 0-1 then rating is Low.
Step 2. Determine ICOLL Dilution Potential (ICOLL DP)	**ICOLL DP =** $(Nload \div EV_{lw}) * ECI_{consec}$ Where N load is the annual total nitrogen input load to the estuary (kg/yr). EV_{lw} is the low tide estuary volume. For unstratified ICOLLs: If answer = >10 then rating is Very High; 5-10 then rating is High; 1-5 then rating is Moderate; 0-1 then rating is Low.

ICOLL SUSCEPTIBILITY (CONTINUED)

Step 3. Determine ICOLL Physical and Nutrient Load Susceptibility

The final physical and nutrient load susceptibility to eutrophication of ICOLLs based on physical and nutrient load characteristics is determined using the ICOLL FP and the ICOLL DP ratings as calculated above, and the following matrix.

		ICOLL Nutrient Dilution potential			
		Very High	High	Moderate	Low
ICOLL Flushing Potential	Very High	Very High Susceptibility	Very High Susceptibility	High Susceptibility	Moderate Susceptibility
	High	Very High Susceptibility	High Susceptibility	Moderate Susceptibility	Low Susceptibility
	Moderate	Very High Susceptibility	High Susceptibility	Moderate Susceptibility	Low Susceptibility
	Low	High Susceptibility	Moderate Susceptibility	Low Susceptibility	Low Susceptibility

ADDITIONAL CONSIDERATIONS.

In addition to the above, seagrass potential may also need to be considered in some situations. This step is still under development and rating thresholds have yet to be established, but the following interim guidance is provided:

To determine the potential for seagrass growth in an ICOLL use the following: Seagrass growth is limited if either the Water Level Fluctuation rating is very high, or water clarity is limiting.

(a) Influence of Excessive Water Level Fluctuations

ICOLL Water Level Fluctuation Factor = ((FW/1000) ÷ EA) * ECI

Where ECI is the proportion of time that the entrance of an ICOLL is closed and is calculated over a long-term period (includes consecutive and non-consecutive days). EA is the estuary area (km^2) when closed. FW is the annual freshwater inflow volume in $ML.yr^{-1}$. The threshold above which seagrass growth is unlikely is yet to be determined.

(b) Influence of Low Clarity

The preferred water clarity for seagrass (*Ruppia* sp.) growth in ICOLLs is an average value of at least 20 percent of the sunlight that strikes the water's surface (incident light) should reach the plant leaves, assuming that the Secchi depth can be approximated to 20% of the surface light (Lorenzen 1972).

TECHNICAL SUPPORTING INFORMATION

Data and supporting information, including worked examples, are presented in Appendix 3.

2. SIDE SUSCEPTIBILITY

Shallow, Intertidal Dominated Estuaries (includes Tidal Lagoon Estuaries, Tidal River Lagoons and Tidal Deltas)

Within NZ, tidal lagoon estuaries (with permanently open mouths) are almost always shallow (<3m), have residence time <3 days, and intertidal area >40% of the total estuary area (some harbours are the exception e.g. Otago Harbour). Although they are too well flushed to have sustained phytoplankton blooms, they can exhibit nuisance growths of opportunistic macroalgae (especially *Ulva* sp. and *Gracilaria* sp.), particularly in the upper estuary tidal flats where flocculation and mud deposition is encouraged (Robertson and Stevens 2013).

The recommended steps for determining the physical and nutrient load susceptibility of shallow tidal lagoon estuaries and the supporting information follows below. It is noted that the thresholds are based on limited data and therefore should be used for preliminary monitoring and "screening-type" management guidance and supported by more detailed site-specific studies for final nutrient load assessments.

Technical Supporting Information

Data and supporting information, including worked examples, are presented in Appendix 4.

Step 1. Determine Flushing Potential (FP)	**ASSETS Approach:** A flushing rating, calculated as freshwater inflow ($m^3.d^{-1}$) divided by estuary volume (m^3) and adjusted for tidal height (m). For FW inflow/Est Vol; Macrotidal (>1.8m): 10^{0}-10^{-2} High, 10^{-3} -10^{-4} Moderate. Mesotidal (0.8m-1.8): 10^{0}-10^{-1} High, 10^{-2} Moderate, 10^{-3}-10^{-4} Low. Microtidal (<0.8m): 10^{0}-10^{-1} High, 10^{-2} Moderate, 10^{-3}-10^{-4} Low.
Step 2. Determine Dilution Potential (DP)	**ASSETS Approach:** For unstratified and minor vertical stratification (e.g. upper estuary and navigation channels) estuaries the DP calculated as: DP = 1 ÷ estuary volume (ft^3) (Note: ASSETS approach uses cubic feet as units for volume) or if estuary stratified then DP = 1 ÷ estuary freshwater layer volume (ft^3). For unstratified estuaries: If answer = 10^{-12}-10^{-13} then rating is High; 10^{-11} then rating is Moderate; 10^{-9}-10^{-10} then rating is Low.

SIDE: SUSCEPTIBILITY (CONTINUED)

Step 3. Determine Physical Susceptibility or Export Potential (EP)

ASSETS Approach: Determine the overall physical susceptibility of an estuary to dilution and flushing by combining the physical susceptibility (FP and DP) information in the following matrix.

Flushing Potential	Dilution potential: High	Dilution potential: Moderate	Dilution potential: Low
High	High EXP & Low Susceptibility	High EXP & Low Susceptibility	Moderate EXP & Moderate Susceptibility
Mod	High EXP & Low Susceptibility	Moderate EXP & Moderate Susceptibility	Low EXP & High Susceptibility
Low	Moderate EXP & Moderate Susceptibility	Low EXP & High Susceptibility	Low EXP & High Susceptibility

Step 4. Determine the Combined Physical and Nutrient Load Susceptibility

Determine how nutrient load susceptibility relates to physical characteristics and trophic state expression in representative NZ SIDE estuaries - under development, Ben Robertson PhD.

It is proposed that the N Load Susceptibility is based on relationships between nutrient load and presence of gross eutrophic zones (i.e. high macroalgal cover/biomass and RPD at surface) in the upper estuary and seagrass for NZ shallow, intertidal dominated estuaries (see subsequent supporting information).

The combined susceptibility of physical and nutrient load factors is determined based on the Physical Susceptibility calculated above, and N Load Susceptibility. To determine the influence of the nutrient areal load ($mgN.m^{-2}.d^{-1}$) on nuisance macroalgal and seagrass growth, use the following thresholds: Very high is >250 High is >50-250, Moderate is 10-50, Low is <10mg.$m^{-2}.d^{-1}$. The physical susceptibility ratings (or export potential) are as indicated above (i.e. ASSETS approach). The combined physical and nutrient load susceptibility is determined from the following matrix.

Physical Susceptibility	N load Susceptibility ($mg/m^2/d$): 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
Mod	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

To estimate the nutrient load, estimates of catchment nutrient loads (supplemented with point source input data) are the logical first source of this data (e.g. NIWA's CLUES Model, SCENY Model - Heggie and Savage (2009), etc) bearing in mind that model data will likely need to be validated, or at least exposed to sensitivity analysis, once major management decisions are being addressed. Once the load is estimated in kgN/yr or kgP/yr, then normalise it to the estuary area (i.e. $mgN.m^2.yr^{-1}$) by the following equation: Areal N load ($mgN.m^2.yr^{-1}$) = N load (kg/yr)/Area Estuary (km^2)

The following table provides narrative guidance on the ecological condition that is likely to result from combined N load and physical susceptibility ratings using the following ecological condition bands that relate to the table above.

Band	A	B	C	D
Ecological Quality	No stress caused by the indicator on any aquatic biota. Healthy seagrass communities present.	A minor stress on sensitive biota caused by the indicator. Some eutrophic symptoms (e.g. macroalgae) but still support healthy seagrass and fish communities.	Moderate stress on a number of aquatic biota caused by the indicator exceeding preference levels for some species and a risk of sensitive biota species being lost or reduced. Macroalgal growth moderate.	Significant, persistent stress on a range of aquatic biota caused by the indicator exceeding tolerance levels. A likelihood of local extinctions of keystone species and loss of ecological integrity. Algal dominated, turbid systems, seagrass absent or reduced.

Optional Supporting Information: Susceptibility to Nutrient Concentrations

Macroalgal blooms can be excessive in SIDE estuaries where high susceptibility habitat is present and DIN values exceed saturation levels for nuisance macroalgae. Although there are limited data for SIDEs (mouth is always open), ECan Avon-Heathcote Estuary data from 2010-2014 suggest the appearance of eutrophic conditions may be unlikely below a TN concentration around 400ugTN/l, but the confidence around this value is low (John Zeldis pers. comm. 2016).

Plew and Barr (2015) highlight a very strong but non-linear relationship between tissue-N content in *Ulva* and its potential growth rate (Björnsäter and Wheeler 1990), but with other factors known to affect growth, in particular light and temperature. Consequently, Plew and Barr (2015) propose draft target ranges of both *Ulva* tissue-N content and potential water DIN concentrations for controlling potential growth (informed from Morand and Briand 1996, Barr et al. 2013) as follows: Low: <28ugN/l, Low-Moderate: 28-70ugN/l, Moderate-High: 70-210ugN/l, High: >210ugN/l. Determination of the eutrophication susceptibility level produced by nutrient concentrations requires additional work before robust predictive relationships can be identified, and the values above are therefore considered to provide interim guidance for broad scale screening, and are not for management and regulatory purposes.

3. SSRTRE SUSCEPTIBILITY

Shallow Short Residence Time Tidal River and Tidal River-Lagoon Estuaries

Shallow, short residence time, often subtidal dominated tidal river estuaries (e.g. Whareama Estuary, Whanganui River Estuary), and tidal river estuaries that exit through a small lagoon (e.g. Toetoes Estuary, Ruataniwha Inlet), are generally so well flushed (high flushing potential i.e. freshwater inflow/estuary volume ratio >0.16 - NIWA Coastal Explorer) that they only express eutrophication symptoms if nutrient loads are relatively high AND any of the following high risk features are present:

- 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. Toetoes Estuary - tidal river plus adjoining lagoon) - for these habitats use a modified SIDE approach.

During prolonged low flow (i.e. drought) periods, eutrophic symptoms of excessive opportunistic macroalgal growths can appear, but are generally removed on the next big flood flow. In general, these estuary types have extremely low eutrophication susceptibilities and can often tolerate nutrient loads an order of magnitude greater than shallow, intertidal dominated estuaries. The recommended steps for determining the physical and nutrient load susceptibility of these estuary types, and the supporting information, follows below. It is noted that the thresholds are based on limited data and therefore should be used for preliminary monitoring and "screening-type" management guidance and supported by more detailed site-specific studies for final nutrient load assessments.

Technical Supporting Information

Data and supporting information, including worked examples, are presented in Appendix 5.

Step 1. Determine Flushing Potential (FP)

ASSETS Approach: A flushing rating, calculated as freshwater inflow ($m^3.d^{-1}$) divided by estuary volume (m^3) and adjusted for tidal height (m). For FW inflow/Est Vol; Macrotidal (>1.8m): 10^0-10^{-2} High, 10^{-3} -10^{-4} Moderate, <10^{-4} Low.

Mesotidal (0.8m-1.8): 10^0-10^{-1} High, 10^{-2} Moderate, 10^{-3}-10^{-4} Low.

Microtidal (<0.8m): 10^0-10^{-1} High, 10^{-2} Moderate, 10^{-3}-10^{-4} Low.

Step 2. Determine Dilution Potential (DP)

ASSETS Approach: For unstratified and minor vertical stratification (e.g. upper estuary and navigation channels) estuaries the DP calculated as: DP = 1 ÷ estuary volume (ft^3) (Note: ASSETS approach uses cubic feet as units for volume) or if estuary stratified then DP = 1 ÷ estuary freshwater layer volume (ft^3).

For unstratified estuaries: If answer = 10^{-12}-10^{-13} then rating is High; 10^{-11} rating is Moderate; 10^{-9}-10^{-10} rating is Low.

Step 3. Determine Physical Susceptibility or Export Potential (EP)

ASSETS Approach: Determine the overall susceptibility of an estuary to dilution and flushing by combining the physical susceptibility (FP and DP) information in the following matrix. Note that EP should be rated as high susceptibility if "high risk" features are present, i.e. deep poorly flushed holes and/or banks or bed lined with stable substrate for attachment of nuisance macroalgal growths.

		Dilution potential		
Flushing Potential		High	Moderate	Low
	High	High EXP & Low Susceptibility	High EXP & Low Susceptibility	Moderate EXP & Moderate Susceptibility
	Mod	High EXP & Low Susceptibility	Moderate EXP & Moderate Susceptibility	Low EXP & High Susceptibility
	Low	Moderate EXP & Moderate Susceptibility	Low EXP & High Susceptibility	Low EXP & High Susceptibility

Step 4. Determine the Combined Physical and Nutrient Load Susceptibility

Given the limited data for tidal river estuaries, determination of the eutrophication susceptibility level produced by nutrient loads and nutrient concentrations requires additional work before robust predictive relationships can be identified. In the interim, tentative guidance on nutrient load susceptibility for shallow, short residence time, tidal river estuaries (whose mouth is always open) is recommended as follows:

- For estuaries with no "high-risk" features; the appearance of eutrophic conditions is unlikely below an N load <2000mgN.m^{-2}.d^{-1}, but the confidence in the level of this thresholds is low. As a consequence, this tentative trigger guideline is suitable only for broad scale screening, and not for management and regulatory purposes.
- For estuaries with "high-risk" features; use the more conservative "high risk TR" ratings used for SIDEs estuary types (see below matrix), but again these should only be used for screening purposes.

		N load Susceptibility (mg/m²/d)			
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
	Mod	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

4. DSDE SUSCEPTIBILITY

Deeper, Longer Residence Time, Subtidal Dominated Estuaries (includes Coastal Embayments, Tidal Lagoons, Tidal Rivers and Fiords)

Mainly subtidal, moderately deep (>3m to 15m mean depth) coastal embayments (e.g. Firth of Thames) and tidal lagoon estuaries (e.g. Otago Harbour), with moderate residence times (>7 to 60 days) can exhibit both sustained phytoplankton blooms, and nuisance growths of opportunistic macroalgae (especially *Ulva* sp. and *Gracilaria* sp.) if nutrient loads are excessive. The latter are usually evident particularly on muddy intertidal flats near river mouths and in the water column where water clarity allows. Deeper, long residence time embayments and fiords are primarily phytoplankton dominated if nutrient loads are excessive. In both cases, it is expected that the ASSETS approach will adequately predict their trophic state susceptibility. Where parts of these estuaries have habitats that are more like other estuary types (e.g. large areas of tidal flats surrounding a river inflow, e.g. Firth of Thames), then it is recommended that the most relevant susceptibility methodologies for that particular estuary part be followed.

The recommended steps for determining the physical and nutrient load susceptibility of such estuaries and the supporting information are presented below. It is noted that the thresholds are based on limited data and therefore should be used for preliminary monitoring and "screening-type" management guidance and be supported by more detailed site-specific studies for final nutrient load assessments.

Technical Supporting Information

Data and supporting information, including worked examples, are presented in Appendix 6.

Step 1. Determine Flushing Potential (FP)

ASSETS Approach: A flushing rating, calculated as freshwater inflow ($m^3.d^{-1}$) divided by estuary volume (m^3) and adjusted for tidal height (m). For FW inflow/Est Vol; Macrotidal (>1.8m): 10^0-10^{-2} High, 10^{-3} -10^{-4} Moderate. Mesotidal (0.8m-1.8): 10^0-10^{-1} High, 10^{-2} Moderate, 10^{-3}-10^{-4} Low. Microtidal (<0.8m): 10^0-10^{-1} High, 10^{-2} Moderate, 10^{-3}-10^{-4} Low.

Step 2. Determine Dilution Potential (DP)

ASSETS Approach: For unstratified and minor vertical stratification (e.g. upper estuary and navigation channels) estuaries the DP calculated as: DP = 1 ÷ estuary volume (ft^3) (Note: ASSETS approach uses cubic feet as units for volume) or if estuary stratified then DP = 1 ÷ estuary freshwater layer volume (ft^3).

For unstratified estuaries: If answer = 10^{-12}-10^{-13} then rating is High; 10^{-11} rating is Moderate; 10^{-9}-10^{-10} rating is Low.

Step 3. Determine Physical Susceptibility or Export Potential (EP)

ASSETS Approach: Determine the overall susceptibility of an estuary to dilution and flushing by combining the physical susceptibility (FP and DP) information in the following matrix. Note that EP should be rated as high susceptibility if "high risk" habitat is present, i.e. deep poorly flushed holes and/or banks or bed lined with stable substrate for attachment of nuisance macroalgal growths.

		Dilution potential		
		High	Moderate	Low
Flushing Potential	High	High EXP & Low Susceptibility	High EXP & Low Susceptibility	Moderate EXP & Moderate Susceptibility
	Mod	High EXP & Low Susceptibility	Moderate EXP & Moderate Susceptibility	Low EXP & High Susceptibility
	Low	Moderate EXP & Moderate Susceptibility	Low EXP & High Susceptibility	Low EXP & High Susceptibility

Step 4. Determine the Combined Physical and Nutrient Input Susceptibility

ASSETS Approach: The pressure from nutrient inputs (called Nutrient Load Influence, NLI) is calculated by comparing nutrients from watershed or land-based (human) inputs with oceanic or natural inputs (either loads or concentrations can be used to calculate the NLI). The NLI is highest when the catchment input is high relative to the ocean input.

The NLI estimation procedure using loads is: **NLI = CL/ (OL + CL)** where:

CL = Catchment N load; OL = Ocean N load (derived from offshore).

The NLI estimation procedure using concentrations (Nutrient Concentration Influence - NCI) is: $\mathbf{NCI = m_h / (m_b + m_h)}$

where:

m_h = DIN concentration derived from catchment (plus salinity influence);

m_b = DIN concentration from offshore.

m_h and m_b are estimated using concentrations as follows: $\mathbf{m_h = m_{in} * (S_o - S_e)/S_o}$ and $\mathbf{m_b = m_{sea} * S_e/S_o}$ where:

m_{sea} = DIN concentration of the ocean; S_e = Salinity of estuary (average ppt); S_o = Salinity of ocean;

m_{in} = DIN concentration in inflow to the estuary (Bricker et al. 2003, p.46).

The final Influencing Factor or Pressure rating (also called OHI in ASSETS) is derived using the following matrix which combines the NLI (see ratings in sidebar) with physical susceptibility to determine overall eutrophication susceptibility.

		Nutrient Load Influence			
		High >0.8	Moderate High >0.5-0.8	Moderate Low >0.2-0.5	Low 0-<0.2
Physical Susceptibility	High	High	Moderate-High	Moderate	Moderate
	Mod	Moderate-High	Moderate	Moderate	Moderate-Low
	Low	Moderate - Low	Moderate-Low	Low	Low

Ratings for Nutrient Load Influence (NLI) are:

Low if <0.2
Mod-Low >0.2-0.5
Mod-High >0.5-0.8
High >0.8

Screening Tool 1 - Scoring Sheet

Scoring Sheet for determining eutrophication susceptibility using physical and nutrient load data

Identify Estuary For Susceptibility Assessment →

Choose Estuary (or Part of Estuary) Type

1. Intermittently Closed/Open Lake or Lagoon (ICOLL)
2. Shallow Intertidal Dominated Estuary (SIDE)
3. Shallow, Short Residence Time Tidal River Estuary (SSRTRE)
4. Deeper, Subtidal Dominated, Estuaries (DSDE)

↓

Determine Susceptibility To Eutrophication

Determine the susceptibility to eutrophication based on physical and nutrient load factors - produces a high, moderate or low susceptibility rating (or in some cases narrative ecological quality bands) as follows.

Estuary Type and Method	**Physical and Nutrient Load Susceptibility** (insert calculated susceptibility)	
1. ICOLL: Nutrient Load Threshold or Physical and Nutrient Load Susceptibility (Two Screening Methods Available)		
(A) Preferred Method: Determine ICOLL Nutrient Load Threshold (Preliminary)		
(a) Shallow lagoon ICOLLs, closure period of months (e.g. Waituna Lagoon).	Method A. preferred	
TN Areal Load (mg/m^2/d); low <10, moderate 10-20, high 20-35, very high >35.	TN Areal Load =________ mg/m^2/d	ICOLL N Susceptibility = _______
TP Areal Load (mg/m^2/d); low <0.55, moderate 0.55-1.5, high 1.5-5.5, very high >5.5.	TP Areal Load = ________ mg/m^2/d	ICOLL P Susceptibility = _______
(b) Low susceptibility ICOLLs, closure period of days to weeks (e.g. Lake Onoke). Currently insufficient data to recommend thresholds but likely an order of magnitude higher than (a) types.		
(B) Least Preferred Method: Determine ICOLL Physical and Nutrient Load Susceptibility	Method B. least preferred	
Step 1. Determine ICOLL Flushing Potential (FP)	FP= _______	
Step 2. Determine ICOLL Dilution Potential (DP)	DP= _______	
Step 3. Determine ICOLL Physical and Nutrient Load Susceptibility		ICOLL Susceptibility = _______
NOTE: Consider also if clarity or fluctuating water levels are limiting macrophyte growth		
2. SIDE: Physical and Nutrient Load Susceptibility (One Screening Method Available)		
Step 1. Determine SIDE Dilution Potential (DP)	DP = _______	
Step 2. Determine SIDE Flushing Potential (FP)	FP = _______	
Step 3. Determine SIDE Physical Susceptibility or Export Potential (EP)	EP = _______	
Step 4. Determine SIDE Nutrient Load Threshold from export potential and TN Areal Load (mg/m^2/d); low <10, moderate 10-75, high 75-250, very high >250.		SIDE Susceptibility = _______
3. SSRTRE: Physical and Nutrient Load Susceptibility (One Screening Method Available)		
Step 1. Determine SSRTRE Dilution Potential (DP)	DP = _______	
Step 2. Determine SSRTRE Flushing Potential (FP)	FP = _______	
Step 3. Determine SSRTRE Physical Susceptibility or Export Potential (EP)	EP = _______	
Step 4. Determine SSRTRE Nutrient Load Threshold from export potential and TN load data. NOTE: Insufficient information to identify robust nutrient load thresholds therefore use interim screening guidance thresholds as follows: (a) Estuaries with no "high risk " habitat; eutrophic conditions unlikely at <2000 mgN/m^2/d. (b) Estuaries with "high risk " habitat, use physical susceptibility and nutrient load matrix to determine nutrient load susceptibility.		SSRTRE Susceptibility = _______
4. DSDE: Physical and Nutrient Load Susceptibility (One Screening Method Available)		
Step 1. Determine DSDE Dilution Potential (DP)	DP = _______	
Step 2. Determine DSDE Flushing Potential (FP)	FP = _______	
Step 3. Determine DSDE Physical Susceptibility or Export Potential (EP)	EP = _______	
Step 4. Determine DSDE Nutrient Load Threshold from export potential and TN load data. NOTE: Insufficient information to identify robust nutrient load thresholds. Interim nutrient load influence can be calculated using nutrient load and physical susceptibility matrix or N load influence equation: Nutrient Load Influence, NLI = CL/ (OL + CL) where: CL = Catchment N load; OL = Ocean N load (derived from offshore). Ratings for nutrient load influence are as follows: low if NLI <0.2, moderate 0.2-0.5, high 0.5-0.8, very high >0.8.		DSDE Susceptibility = _______

Figure 3. Screening Tool 1 - Scoring Sheet.

Supporting Technical Information for Screening Tool 1.

FOR DETERMINING EUTROPHICATION SUSCEPTIBILITY USING PHYSICAL AND NUTRIENT LOAD DATA

These appendices have been developed as a skeleton of information (including available NZ estuary data) that support the recommended ETI approaches for determining estuary eutrophication susceptibility and trophic condition. It is anticipated that they will be expanded upon as new information becomes available.

TOOL 1: APPENDIX 1. OVERSEAS APPROACHES TO SUSCEPTIBILITY

BACKGROUND

OVERSEAS APPROACHES AS A FRAMEWORK FOR THE NZ APPROACH

The approach taken in the ETI is a modification of two overseas screening approaches, the US based ASSETS toolbox (Bricker et al. 1999) which was primarily developed for larger and deeper estuaries than those which dominate the NZ situation, and the Australian NSW ICOLLs approach (Haines et al. 2006). In summary, these approaches use freshwater inflow volumes, estuary volume, mouth open/closed regimes, and tidal range data to estimate the potential for flushing and dilution of nutrients (and hence nutrient retention) within the estuary. These two overseas approaches are summarised in the following sections.

MODIFICATIONS TO ACCOUNT FOR NZ ESTUARY TYPES

When combined with the annual nutrient input load, the ASSETS approach provides a coarse estimate of the extent to which the N load is diluted and retained in the water column. It therefore provides a reasonably reliable indicator of trophic status in estuaries where the primary drivers of eutrophication are water column nutrient concentrations and water residence time (i.e. "deeper subtidal dominated, longer residence time estuaries" and "shallow short residence time tidal river estuaries").

However, the ASSETS approach is less reliable for estuaries where depth, currents and bed conditions are major drivers (i.e. in NZ's dominant "SIDE" and "ICOLL" estuary types). In order to account for such effects in these two estuary types, the ETI introduces additional estuary physical characteristics into the susceptibility analysis including opening/closing regimes in ICOLLs, and sediment characteristics (especially mud deposition zones) in SIDE systems. The strong inter-relationship of eutrophication (expressed as macroalgal cover) and presence of muds (expressed as soft muds and very soft mud) in these latter estuary types is clearly demonstrated in substrate and macroalgal habitat maps for New River Estuary (Figures A1 and A2).

The modifications also include relevant nutrient load/estuary ecological response relationships, that are subsequently used to establish nutrient load thresholds for common NZ estuary types. Effectively, this introduces an estuary type classification into the susceptibility toolbox which is based on physical and hydrologic characteristics and their influence on the expression of nutrient load related impacts such as macroalgal and phytoplankton blooms.


Doubtful Sound


Bird banding, Waimea Estuary


Porirua Harbour - synoptic sediment sampling

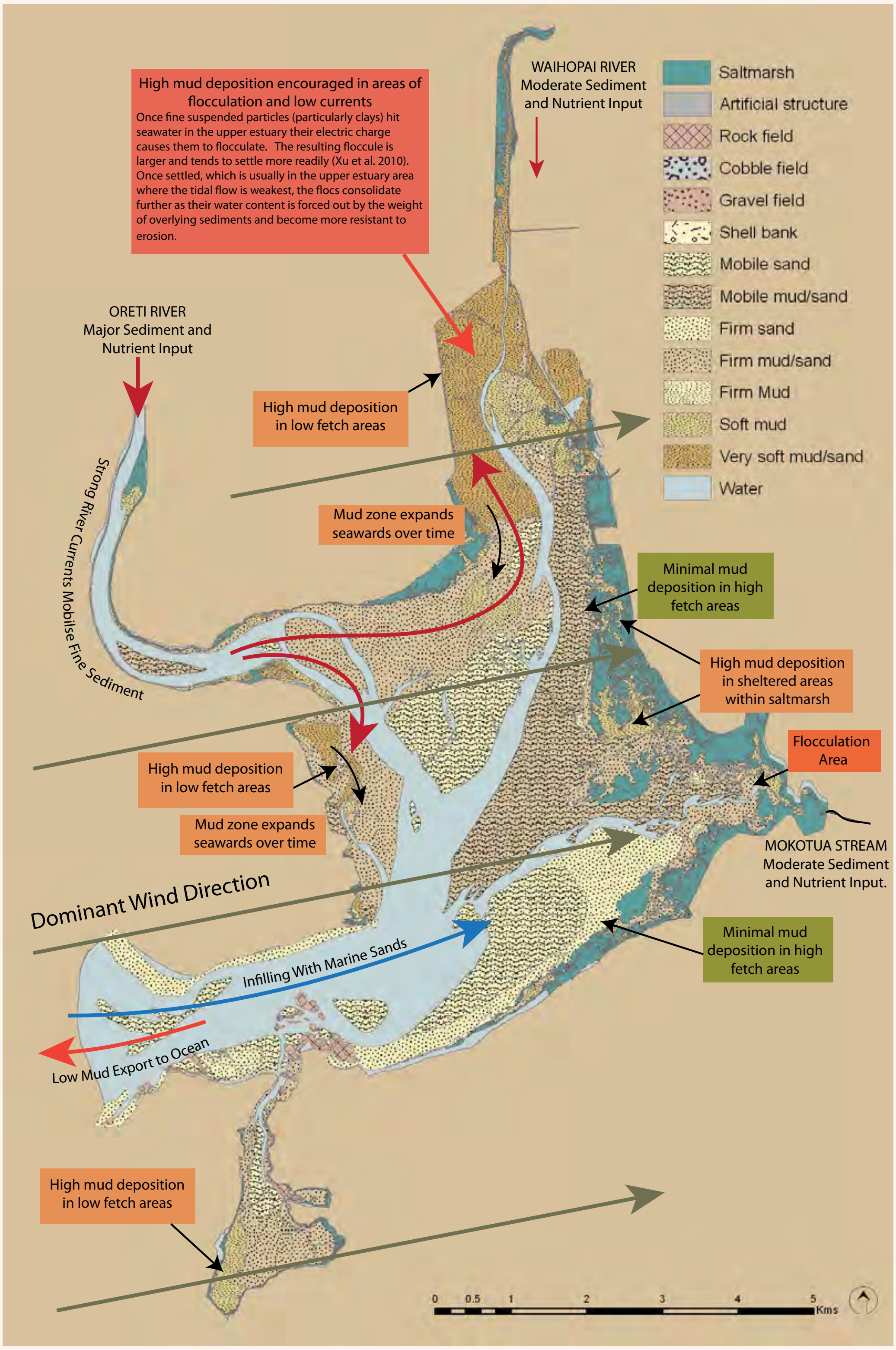

Phytoplankton bloom, Motupipi Estuary


Healthy seagrass beds, Freshwater Estuary


Low density seagrass under stress, New River Estuary


Macroalgal blooms (*Ulva* and *Gracilaria*), New River Estuary


Black toxic sulphides, New River Estuary



High mud deposition encouraged in areas of flocculation and low currents

Once fine suspended particles (particularly clays) hit seawater in the upper estuary their electric charge causes them to flocculate. The resulting floccule is larger and tends to settle more readily (Xu et al. 2010). Once settled, which is usually in the upper estuary area where the tidal flow is weakest, the flocs consolidate further as their water content is forced out by the weight of overlying sediments and become more resistant to erosion.

Figure A1. New River Estuary substrate type and conceptual diagram of processes causing fine sediment and bound nutrient deposition (modified from Stevens and Robertson 2012).

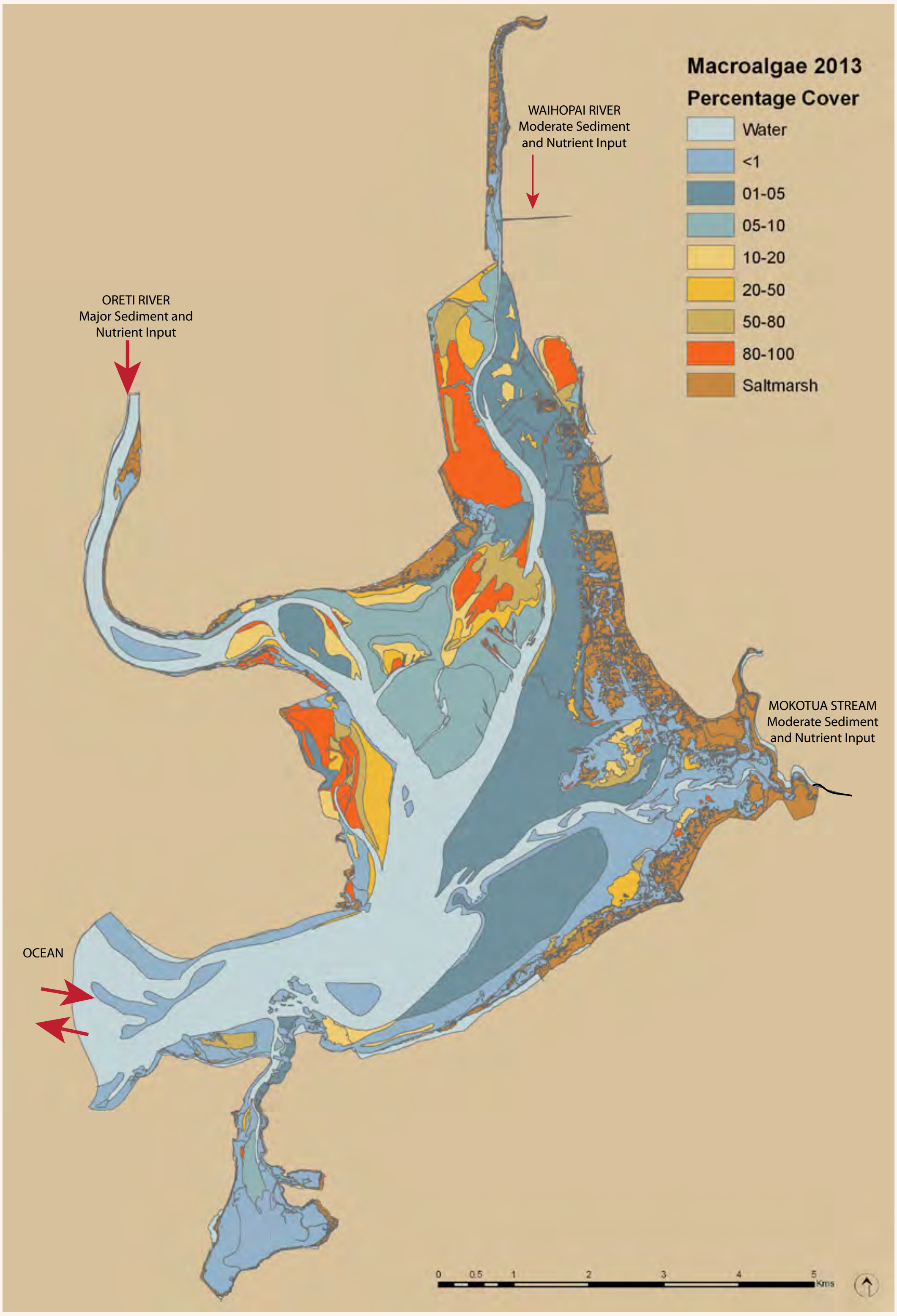


Figure A2. New River Estuary macroalgal cover 2013 (Stevens and Robertson 2012) highlighting relationship between deposition zones and macroalgal density.

1.1 ASSETS APPROACH TO ESTUARY SUSCEPTIBILITY AND RELEVANCE TO NZ ESTUARIES

A relatively simple tool for characterising estuary physical and nutrient load susceptibility to eutrophication is included in the ASSETS toolbox (Bricker et al. 1999). This component takes into account stratification, estuary volume, freshwater inflow, and tidal range, in two physical susceptibility indicators "dilution potential" and "flushing potential" and nutrient concentration or load susceptibility in the "Influencing Factor". Such a limited range of physical susceptibility indicators was considered appropriate in the US because the dataset used to derive the susceptibility response relationships for ASSETS was directed at large, subtidally dominated estuaries. The ASSETS dataset consisted of 138 US estuaries which were primarily subtidal, open, 7.5m mean depth, long residence time, large coastal embayments which expressed moderate to high eutrophic symptoms (Table A1). The most commonly occurring eutrophic symptom was high spatial coverage and frequency of elevated chlorophyll a levels (i.e. phytoplankton), although most estuaries also exhibited at least one other moderate to high symptom (e.g. dissolved oxygen).

Table A1. Comparison of main hydro-morphological characteristics (mean values) of US estuaries and a typical NZ shallow, intertidal dominated estuary.

Region	Depth (m)	Area (km^2)	Volume (10^6m3)	Tidal Range (m)	Catchment Area (10^3 km^2)
US estuaries (mean values of 140 estuaries)	7.5	541	4702	1.3	20
New River Estuary (Southland, NZ)	2	41	74	2.2	4.3

However, the susceptibility of smaller volume estuaries (e.g. Basque estuaries (Europe), California, and NZ), can frequently be underestimated using the ASSETS approach (Garmendia et al. 2012). For example,

- The physical susceptibility rating for New River Estuary, a typical NZ shallow, short residence time, intertidal dominated, tidal lagoon estuary, was estimated as "moderate" using the ASSETS approach, which contradicts findings that it is very susceptible to upper estuary macroalgal blooms because of its large intertidal area in the main estuary deposition zone (Robertson and Stevens 2013).
- The physical susceptibility rating for Waituna Lagoon, a typical NZ shallow ICOLL whose mouth closes for months, was estimated as "low-moderate" using the ASSETS approach, which contradicts findings that it is very susceptible to widespread macroalgal blooms because of its strong tendency to retain nutrients because of mouth closure.

A discussion of the three ASSETS physical susceptibility factors, dilution potential, flushing potential and influencing factor, in relation to their relevance to NZ estuary types is as follows:

A. Dilution Potential (DP)

The influence of dilution on nutrient inputs to an estuary (called "dilution potential" in the ASSETS approach - Bricker et al. 1999), is dependent on the volume of the estuary available for nutrient dilution. For unstratified estuaries the dilution potential is directly proportional to the volume of the estuary and for estuaries that stratify, only the freshwater fraction of the volume is used to derive the rating. Basically, the equation for estimating dilution potential is as follows:

For unstratified and minor vertical stratification (e.g. upper estuary and navigation channels) estuaries, the DP is calculated as:

DP = 1 ÷ estuary volume (ft^3) (Note: ASSETS approach uses cubic feet as units for volume)
or if the estuary is stratified then DP = 1 ÷ estuary freshwater layer volume (ft^3)

The rating thresholds for dilution potential are as follows:

INDICATOR	Potential to Dilute Nutrients				
	Very Low	Low	Moderate	High	Very High
Dilution Potential	not assigned	$1x10^{-8}$ to $1x10^{-9}$ or 10^{-9} to 10^{-10}	>$1x10^{-9}$ to $1x10^{-11}$ or 10^{-11}	>$1x10^{-11}$ to $1x10^{-12}$ or 10^{-12} to 10^{-13}	Not assigned

The rating implies that if dilution is high (because of the high estuary volume) then the nutrient supply to fuel opportunistic nuisance algal growth is limited, and eutrophication is unlikely.

TOOL 1: APPENDIX 1. OVERSEAS APPROACHES (CONTINUED)

However, because the ASSETS approach was developed for much greater volume estuaries (>2.8 million m^3) than most NZ estuaries, its use is only appropriate for NZ's larger volume estuaries i.e. fiords, embayments, most tidal lagoons and some of the larger tidal rivers (Table A2). It clearly should not be used on NZ estuaries with an estuary volume of <2.8 million m^3. Table A2 shows that over 50% of NZ estuaries are too small to fit in the ASSETS three available dilution potential rating categories and therefore require further development if the ASSETS criteria are to be used to accurately assess smaller volume NZ estuaries. Potentially, there are two main approaches to achieve this:

- One method would be to calculate appropriate dilution potential ratings for the whole NZ estuary data set so that it was relevant to all NZ estuary types.
- Another method is to include additional physical susceptibility indicators and ratings (additional to the two used in the ASSETS approach, i.e. dilution potential and flushing potential) that are appropriate for the smaller volume estuaries and ICOLLs, and to place them in the currently unassigned "very low" DP category. This latter approach is basically to create separate criteria for nutrient retention based on estuarine typology. A typology component is currently a high priority for development of the ASSETS methodology (Dalton et al. 2006).

Table A2. Dilution potentials of NZ estuary types.

Main Estuary Types	ASSETS Dilution Potential Thresholds	Dilution Potential (1/estuary volume, ft^3)	Number of NZ Estuaries in DP Category*
Fiord	High	$<1x10^{-12}$ or 10^{-13}	1
Large Embayments, Fiords	High	$1x10^{-12}$ to $<1x10^{-11}$ or 10^{-12}	9
Embayments, Fiords	Moderate	$1x10^{-11}$ to $<1x10^{-10}$ or 10^{-11}	22
Tidal Lagoons	Low	$1x10^{-10}$ to $<1x10^{-9}$ or 10^{-10}	48
Tidal Lagoons and Tidal Rivers	Low	$1x10^{-9}$ to $<1x10^{-8}$ or 10^{-9}	142
Tidal Rivers and Small Embayments and Tidal Lagoons	Not assigned	$1x10^{-8}$ to $<1x10^{-7}$ or 10^{-8}	164
Tidal Rivers and Streams - small	Not assigned	$1x10^{-7}$ or greater	55

* number of NZ estuaries that fit in each dilution potential category, with data sourced primarily from NIWA's Coastal Explorer database. Note that this database excludes hundreds of small tidal river estuaries, many of which have intermittently closed/open mouths and have dilution potentials $>10^{-9}$. For the purposes of this calculation, it was assumed that all estuaries were not significantly salinity stratified, which is probably true for all except for fiords, some embayments and small areas in the upper reaches of the other estuaries.

B. Flushing Potential (FP)

A major influence on the flushing of nutrient inputs out of an estuary, instead of them being retained, is the freshwater inflow volume and tidal range in relation to the estuary volume. The degree to which nutrients are flushed out of the estuary by freshwater inflow and tidal currents generally declines as the estuary volume increases. Consequently, for a given tidal range, a low freshwater inflow/estuary volume ratio (called Flushing Potential (FP) in the ASSETS approach) indicates high retention of catchment nutrient inputs and a high susceptibility to eutrophication.

For example, it can generally be concluded that nutrient retention will be higher within an estuary that has a higher FP compared to one with a lower FP. Figure A3 shows flushing potentials typical of a range of NZ estuary types. The equation for estimating flushing potential is as follows:

> Flushing Potential = freshwater inflow ($m^3.d^{-1}$) divided by estuary volume (as m^3 in this case) and adjusted for tidal height (m).

The rating thresholds for flushing potential are as follows:

Flushing Potential Indicator	Potential for Nutrient Flushing to Ocean				
	Very Low	Low	Moderate	High	Very High
Macrotidal (>1.8m)	Not Assigned	Not Assigned	10^{-3}-10^{-4}	10^{0}-10^{-2}	Not Assigned
Mesotidal (0.8m-1.8m)	Not Assigned	10^{-3}-10^{-4}	10^{-2}	10^{0}-10^{-1}	Not Assigned
Microtidal (<0.8m)	Not Assigned	10^{-3}-10^{-4}	10^{-2}	10^{0}-10^{-1}	Not Assigned

Note: components modified to account for NZ estuary types with high freshwater inflow to a small volume estuary.

The ASSETS methods for determining flushing potential is expected to be relatively robust across the deeper, larger volume NZ estuaries (given that ASSETS was based on such estuary data), but as in the US, it needs further development to account for estuaries where the tidal range is nearly equal to the depth the estuary (Dalton et al. 2006). For example, if two estuaries have the same tidal range, freshwater inflows and volumes, but one is 10m deep and the other 1.5m deep, then nutrient retention is clearly likely to be less in the latter case, given that it loses nearly all of its water at low tide.

Within NZ, these latter shallow estuaries (<3m deep) are the dominant estuary type (224 estuaries <3m deep and 210 >3m deep in NIWA's Coastal Explorer database, noting that this database excludes hundreds of small shallow tidal river estuaries). In such cases (smaller, shallow estuaries that almost completely empty out during low tide), the ASSETS determined flushing potential is likely to be an under-estimate, e.g. moderate instead of high.

In order to rectify this issue for shallow NZ estuaries, it is recommended that all tidally flushed NZ estuaries with a mean depth <3m, be categorised in the unassigned "very high" flushing potential category in the ASSETS rating. However, other factors can encourage nutrient retention, even in situations where the flushing potential is relatively high, and consequently it is also recommended that these other factors be accounted for determining the potential for nutrient retention, in particular, deposition of nutrient-bound sediment in intertidal and shallow water "deposition zones" and subsequent resuspension, and/or deposition in deep holes in otherwise shallow estuaries.

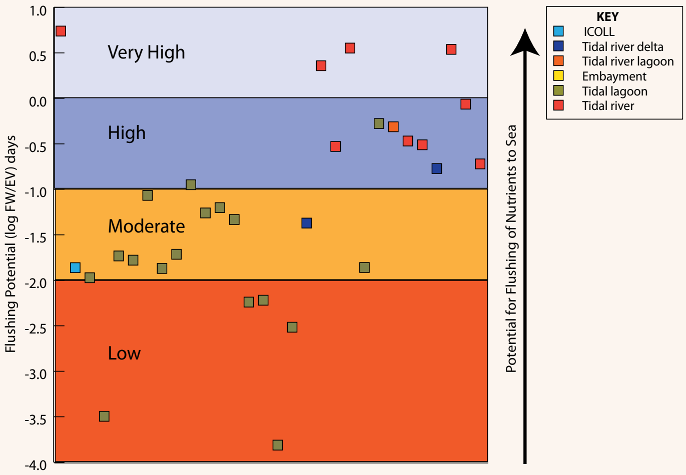


Figure A3. Flushing time for a range of NZ estuary types (source, NIWA Coastal Explorer).

Combined Dilution and Flushing (called Export Potential in ASSETS)

In the ASSETS approach, determining the ***overall susceptibility of an estuary to dilution and flushing***, involves combining the physical susceptibility information in the following matrix.

		Dilution potential		
Flushing Potential		High	Moderate	Low
	High	HIgh EXP & Low Susceptibility	HIgh EXP & Low Susceptibility	Moderate EXP & Moderate Susceptibility
	Mod.	HIgh EXP &Low Susceptibility	Moderate EXP & Moderate Susceptibility	Low EXP &Susceptibility
	Low	Moderate EXP & Moderate Susceptibility	Low EXP &High Susceptibility	Low EXP &High Susceptibility

C. Influencing Factor (Nutrient Load Potential)

In the ASSETS approach, determining the ***overall susceptibility of an estuary to nutrients***, involves combining the physical susceptibility information with a measure of the magnitude of the nutrient loads entering the estuary. Two approaches have been put forward, using loads or using concentrations, but in both, the magnitude of the nutrient loads/concentrations rating is undertaken by a method that is unrelated to data on the biological effects of the nutrients in the estuary. Instead, the rating is determined as the ratio of land-based to oceanic plus land-based nitrogen inputs, with a high rating indicating primarily land-based inputs (Bricker et al. 2003, Ferriera et al. 2011).

TOOL 1: APPENDIX 1. OVERSEAS APPROACHES (CONTINUED)

The Nutrient Load Influence (NLI) estimation procedure for loads is as follows: **NLI = CL/ (OL + CL)** where:

CL = Catchment N load; OL = Ocean N load (derived from offshore)

The Nutrient Concentration Influence (NCI) estimation procedure for concentrations is: $\mathbf{NCI = m_h / (m_b + m_h)}$ where:

m_h = DIN concentration derived from humans in catchment;
m_b = DIN concentration from offshore.

To estimate m_h and m_b using concentrations $\mathbf{m_h = m_{in} * (S_o - S_e)/S_o}$ and $\mathbf{m_b = m_{sea} * S_e/S_o}$ where:

m_{sea} = DIN concentration of the ocean; S_e = Salinity of estuary (average ppt); S_o = Salinity of ocean;
m_{in} = DIN concentration in inflow to the estuary (Bricker et al. 2003, p.46).

The thresholds and rating categories used to determine the susceptibility to nutrients is presented in Table A3.

Table A3. List of thresholds and rating categories used to determine the nutrient load influencing factor.

Class	Threshold	ASSETS Score
Low	0 to <0.2	5
Moderate Low	>0.2-0.4	4
Moderate	>0.4-0.6	3
Moderate High	>0.6-0.8	2
High	>0.8	1

The Bricker et al. (1999) approach for large volume US estuaries approach was later modified by Borja et al. (2006) for smaller volume Basque estuaries and used to assess the trophic state of the smaller Basque estuaries by firstly calculating the total N load normalised for estuary area (i.e. areal N load) and then assigning it into one of four categories (low, moderate, high or very high - see matrix below) based on expert opinion. Pressure on the estuary from nutrients was then assessed by combining the nutrient export potential (dilution potential and flushing time), with nutrient load data, using ratings shown in the following matrix.

		N load (mg/m^2/d)			
		Very High >300	High 200-300	Moderate 100-200	Low <100
Export Potential	Low	Very High Pressure	High Pressure	High Pressure	Moderate Pressure
	Mod.	Very High Pressure	High Pressure	Moderate Pressure	Low Pressure
	High	High Pressure	Moderate Pressure	Moderate Pressure	Low Pressure

TOOL 1: APPENDIX 1. OVERSEAS APPROACHES (CONTINUED)

1.2 BACKGROUND TO NSW ICOLLS APPROACH TO SUSCEPTIBILITY AND RELEVANCE TO NZ ESTUARIES

Like the US ASSETS approach, studies of Australian ICOLLs indicate that physical susceptibility of ICOLLs to eutrophication and sedimentation can be estimated by morphometric and hydraulic parameters, such as area, volume, shape and tidal inflow. However, unlike ASSETS the Australian approach includes the proportion of time that the entrance is either open or closed, and water level, as key physical factors. For Southeast Australian ICOLLs (Haines et al. 2006), these parameters have been used to define three separate factors that each measures one aspect of the natural sensitivity, or vulnerability, of an ICOLL to external loads and other inputs as follows (see Table A4 below for details on calculations):

- **Evacuation Factor**. A measure of how efficiently an ICOLL can remove nutrients and sediment from the estuary, or inversely how efficiently an ICOLL can retain nutrients and sediment.
- **Dilution Factor**. A measure of how efficiently a lagoon dilutes its nutrient and sediment loads.
- **Assimilation Factor**. A measure of the degree of the water level variability in a lagoon, which can subsequently influence the natural biological processes (particularly seagrass growth) and the associated capacity to assimilate or accommodate external inputs.

The approach for identifying the physical and nutrient load susceptibility of a particular ICOLL basically involves estimating the susceptibility for each of these three factors using appropriate equations and classification thresholds (A, B, C and D, with A being the most sensitive). The thresholds were developed from physical and nutrient load data for 8 NSW ICOLLs representative of the full gradient of NSW ICOLLs (vary in size from 0.01 to 10km^2). Assignment of classifications (A to D) for each factor was based on an equal division of the approximate maximum numerical value (the maximum was assigned as the minimum number in the uppermost, i.e. most sensitive, range) for that factor measured within the NSW ICOLL data set. Haines et al. (2006) also suggests that a similar approach could be used to assess the physical and nutrient load susceptibility of other estuary types.

However, although the results provide a useful relative measure of eutrophication susceptibility for NSW ICOLLs, they are inappropriate for direct application to NZ ICOLLs for the following reasons, but are applicable if modified:

- NZ ICOLLs include some that are much larger (vary in size from 0.002 to 198km^2) than the NSW data set, and therefore the classifications would need to be modified for the NZ situation.
- The NSW classifications lack the validation of susceptibility/trophic response relationships and therefore provide only a relative classification of overall susceptibility. Clearly, the classifications would be more useful in the NZ context if trophic status data was used to help choose appropriate classification boundaries.
- The NSW approach to setting the Evacuation Factor involves estimation of the tidal flushing and overall time the lagoon is closed (i.e. total days per year) for a given lagoon shape and volume, but it ignores two other key elements that drive nutrient retention, the extent of freshwater flushing, and the maximum period of time (i.e. consecutive days) that the ICOLL is closed to the sea. Modification of the Evacuation Factor equation to include the effects of tidal flushing, shape, freshwater inflow, volume, and consecutive days the lagoon is closed per year is expected to provide a more robust estimation of the physical susceptibility of NZ ICOLLs to nutrient retention. A summary of the recommended modifications are identified in Table A4.

Table A4. Calculations for Physical and Nutrient Load Susceptibility of Australian ICOLLs

Evacuation Factor (EF) [called Flushing Potential in Recommended NZ ICOLLs Approach]

The first factor (called the Evacuation Factor) is a measure of how efficiently a coastal lagoon can remove pollutants or other inputs through tidal flushing (i.e. the tidal flushing efficiency). The Evacuation Factor is defined as: _Evacuation Factor = [shape function * tidal prism ratio * (1 – ECI)]_$^{-1}$. Relatively large Evacuation Factor values indicate lagoons that have a poor tidal flushing efficiency, and thus cannot physically evacuate pollutants and other inputs from the water as well as other similar lagoon systems. ICOLLs with larger Evacuation Factors are considered to be more sensitive, or vulnerable to external inputs.

- **Shape Function (SF)** is as follows: ICOLLs area of less than 0.15 km^2, SF = (4/0.15) *Area*Perimeter^{-1}. Between 0.15 and 0.8 km^2, SF = {4 + 6* [(Area - 0.15)/0.65)]} *Perimeter^{-1}. Greater than 0.8 km^2, SF = {10 + 40* [(Area - 0.8)/9.2)]} *Perimeter^{-1}. Note that these functions are based on data for NSW ICOLLs, and although NZ ICOLL SFs are likely to be similar, it is recommended that in the longer term SFs for NZ ICOLLs be independently calculated.
- **The Inverted Tidal Prism Ratio (TPR)** = tidal prism volume/ (estuary volume + tidal prism volume). The TPR is designed to account for tidal mixing when the lagoon is open, i.e. TPR provides a coarse estimate of the degree of tidal mixing of an estuary, as it compares the volume of the incoming marine water (i.e. the tidal prism) with the resident volume of the waterway. However, given that some estuaries are not fully mixed during each tide, the TPR can significantly over-estimate the degree of tidal mixing within an estuary.

TOOL 1: APPENDIX 1. OVERSEAS APPROACHES (CONTINUED)

Table A4. Calculations for Physical and Nutrient Load Susceptibility of Australian ICOLLs (continued)

- **The Entrance Closure Index (ECI)** as put forward by Haines et al. (2006) is the proportion of time that the entrance of an ICOLL is closed and is calculated over a long-term period, and as such, represents typical, averaged entrance conditions. For example, Waituna Lagoon was closed for 2606 days over a period of 4745 days between 1997 and 2010, giving an ECI of 2606/4745 = 0.55 (i.e. it is more closed than open). The longest period of closure was 364 consecutive days and the shortest was 40 days (ES data), the mean was 168 days. The ECI, or proportion of the time the ICOLL is closed, directly influences the EF, or retention potential. However, in the Haines approach, the proportion of time closed includes both consecutive and non-consecutive days closed, which means that an ICOLL that closes for 162 days in a year (ECI 0.5) but is open for a week then closes for a week, produces the same ECI as another ICOLL that closes for 162 consecutive days in a year. Clearly, nutrient retention in the latter system is likely to be greater because build-up in nutrient concentrations to levels that encourage algal blooms is encouraged, which implies increased nutrient sedimentation and retention. In addition, because of the threat to the ecology from just one or two long term closures (e.g. loss of seagrass beds and the difficulty in getting them to grow again), it is recommended that the longest closure periods be used to derive the ECI. Consequently, the ECI has been modified to the following: ECI_{evac} = the longest proportion of time that the entrance of an ICOLL is closed over consecutive days and is calculated over a long-term period.

Recommended Evacuation Factor (modified for NZ ICOLLS): The flushing potential component in the ASSETS (Bricker et al. 1999) physical susceptibility to eutrophication approach, involves estimation of the freshwater flushing in relation to lagoon volume for given tidal ranges. The Haines approach, although it includes the tidal component, does not take the freshwater flushing component as a nutrient retention factor (it only includes it as a nutrient assimilation factor, or in other words a factor that accounts for the influence of large water level increase meaning greater likelihood of mouth opening and more stressful conditions for seagrass growth). Introducing freshwater inflow volume as a factor in the Evacuation Function has therefore been undertaken for the NZ approach. The recommended equation for the Evacuation Factor or Flushing Potential (FP) for application to NZ ICOLLs is as follows:

$$\text{ICOLL FP} = (\text{ECI}_{evac}\ \text{consecutive days/yr})/(\text{Freshwater Inflow/Volume})$$

Dilution Factor

The Dilution Factor describes the efficiency of an ICOLL to receive and accommodate inputs from the catchment without significant impact on the resident condition of the waterway. Physical dilution is the primary mechanism controlling the efficiency of the ICOLL to receive and accommodate catchment inputs. Therefore, the Dilution Factor is essentially a comparison between catchment nutrient input loads and the resident volume of the lagoon. It is assumed that when the entrance is open, much of the catchment load is advected to the ocean. As such, the Dilution Factor is adjusted to consider only the proportion of time that the entrance is closed (i.e. the ECI), and that the lagoon is the terminus for all catchment runoff. Lagoons with relatively large Dilution Factors represent systems that have smaller resident volumes and/or larger catchments, and as such, are not as able to dilute inputs as effectively as lagoons with large volumes and/or small catchments (and are defined by relatively smaller Dilution Factors). Lagoons with larger Dilution Factors are considered to be more sensitive, or vulnerable, to external inputs. It is noted that the dilution factor in this approach differs from the ASSETS dilution potential approach in that the former directly accounts for dilution of the catchment nutrient load whereas the latter only indirectly addresses it (i.e. through the estuary volume). The Dilution Factor is defined as: *Dilution Factor = catchment runoff pollutant load (av. annual) * waterway volume*$^{-1}$ ** Entrance Closure Index* ECI. The Dilution Factor has units of mgL^{-1}, and essentially represents the accumulated pollutant concentration within the lagoon that is directly attributable to the average annual catchment runoff load. The Dilution Factor value does not represent a real concentration in the lagoon, but rather, a hypothetical or "potential" concentration assuming pollutant loads are retained and accumulated within the same fixed volume of resident water.

Recommended Dilution Factor for NZ ICOLLS: Dilution Factor is defined as (i.e. includes only maximum consecutive days of closure in ECI calculation): *Dilution Factor = catchment runoff pollutant load (av. annual) * waterway volume*$^{-1}$ ** Entrance Closure Index* ECI_{evac}.

Assimilation Factor

The Assimilation Factor is a de facto measure of the average annual water level variation of an ICOLL. The Assimilation Factor is similar to the Dilution Factor, but addresses the volumetric contribution of catchment inputs rather than pollutant loads, and compares the runoff volume to the waterway area rather than the resident volume of the lagoon. The Assimilation Factor is defined as: *Assimilation Factor = Catchment runoff volume (av. annual) * Waterway Area*$^{-1}$ ** Entrance Closure Index* ECI_{assim}. The Assimilation Factor has dimensions of metres, and represents the effective total average annual water level rise in the lagoon. As water levels in ICOLLs only rise when the entrance is closed to the ocean, the Assimilation Factor has been adjusted to consider only the proportion of volumetric catchment runoff that occurs when the entrance is closed (i.e. includes the ECI_{assim}). The ECI_{assim} is the proportion of time the entrance is closed (including both consecutive and non-consecutive days). Lagoons with larger Assimilation Factors have a more variable water level, which results in a less stable physical environment. Therefore, lagoons with larger Assimilation Factors are considered to be more sensitive, or vulnerable, to external inputs. Lagoons with higher Assimilation Factors would tend to have relatively rapid water level rises and would breakout often, which in some respects is considered to 'reset' the aquatic biological environment (as pelagic organisms can be flushed from the system, while epiphytes, macrophytes and benthos can become exposed to the atmosphere). The rate of water level rise in these lagoons is likely to exceed a critical rate for the establishment of seagrass (which may be defined by an Assimilation Factor value of about 10 (Haines et al. 2006). Note that water clarity in such rapid breakout ICOLLs is also often limiting for seagrass growth, particularly if the catchment is developed (e.g. Lake Onoke).

Recommended Assimilation Factor for NZ ICOLLS: The Assimilation Factor is defined as: *Assimilation Factor = Catchment runoff volume (av. annual) * Waterway Area*$^{-1}$ ** Entrance Closure Index* ECI_{assim}.

TOOL 1: APPENDIX 2. BACKGROUND TO DEVELOPING NUTRIENT LOAD/ESTUARY RESPONSE RELATIONSHIPS

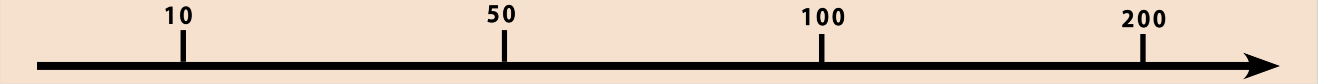
2.1 DEVELOPMENT OF NUTRIENT LOAD/ESTUARY RESPONSE RELATIONSHIPS

As a result of limitations in available data and uncertainties in the N concentration/estuary response relationships (particularly for shallow, intertidal dominated estuaries), the ETI has adopted nutrient loads as the primary stressor, and included nutrient concentrations as a supporting stressor. The development of these relationships and criteria can be undertaken using one or more of three broad approaches as follows:

1. Reference Estuary Statistical Approach (not recommended)
In this approach, ecological gradient thresholds are based on a statistical analysis of current nutrient loads to estuaries (or their nutrient concentrations), e.g. estuaries with the lowest 5% of N loads fit in the minimal eutrophication category without consideration of the actual trophic state of those low N load estuaries. Because this approach ignores the relationship between nutrient levels and estuary condition it is not recommended for setting nutrient limits in NZ estuaries.

2. Empirical Stressor/Response Approach (recommended)
In this approach, the estuary ecological response to nutrient loads along a condition gradient (i.e. “minimally eutrophic” to “very highly eutrophic”) is obtained by selecting example estuaries of a similar type (i.e. estuaries that are expected to have similar ecological responses to nutrient loads or concentrations, for example shallow, intertidal dominated estuaries), that are exposed to different nutrient loads. This approach (see figure below) works well where there are sufficient estuary situations to populate the full ecological gradient, but can also be used to produce a single upper limit threshold in situations where data are available for this section of the ecological gradient only. The estuary condition response is generally identified using appropriate condition indicators (e.g. macroalgal biomass, RPD, macroinvertebrates, TOC, etc.) and including both magnitude and spatial distribution in their interpretation. Such an approach is currently being undertaken as a key step in developing nutrient and sediment load limits for Southland’s shallow, intertidal dominated estuaries (Nick Ward, Freshwater/Marine Science Leader, Environment Southland, pers. comm. 2015).

Nutrient Load (mg.m^{-2}.d^{-1}) [values are for illustrative purposes]



A Minimal Eutrophication	B Moderate Eutrophication	C High Eutrophication	D Very High Eutrophication
Ecological communities are healthy and resilient.	Ecological communities are slightly impacted by additional algal growth arising from nutrients levels that are elevated.	Ecological communities highly impacted by macroalgal biomass elevated well above natural conditions. Water clarity limits macrophytes.	Excessive algal growth making ecological communities at high risk of undergoing a regime shift to a persistent, degraded state without macrophyte/seagrass cover.

3. Modelling Approach (recommended)
This cause-effect approach involves mechanistically modelling the factors of concern and linking them back to nutrient loads and other co-factors controlling response (e.g. hydrology, grazers, denitrification, etc.). To date, this approach has not yet been used extensively for deriving nutrient load limits for NZ estuaries, but it was recently used to derive nutrient load limits for the Southland eutrophic ICOLL, Waituna Lagoon (Waituna Lagoon Technical Group 2013). Overseas, the modelling approach is widely used, ranging from simple statistical models to full numerical ecosystem models (e.g. Valiela et al. 2004). If nutrient loads are being set for regulatory, rather than screening purposes, then it is important to ensure sufficient precision is built into the relationship between nutrient loading and ecological response. For example, while a relationship between macroalgae and nutrient loads may be significant and used to develop a simple estuary statistical screening model, the model will lack precision and be inappropriate for management use unless other supporting indicators are included. In particular, the predictive capability of these models can be improved through inclusion of: i. a hydrodynamic and sedimentation component (both are strongly linked to eutrophication susceptibility), ii. components known to mitigate the effects of eutrophication (e.g. denitrification etc.) and iii. other statistical relationships that support the key nutrient load/primary indicator response relationship (e.g. macrofauna, sediment RPD, TOC etc).

This information could be incorporated into a regional estuary type-specific model for scenario analysis of various nutrient loading rates and their expected estuarine response. An example of key factors that can be considered in such a modelling approach is summarised in Table A5, and a conceptual diagram of key components of the model in Figure A4.

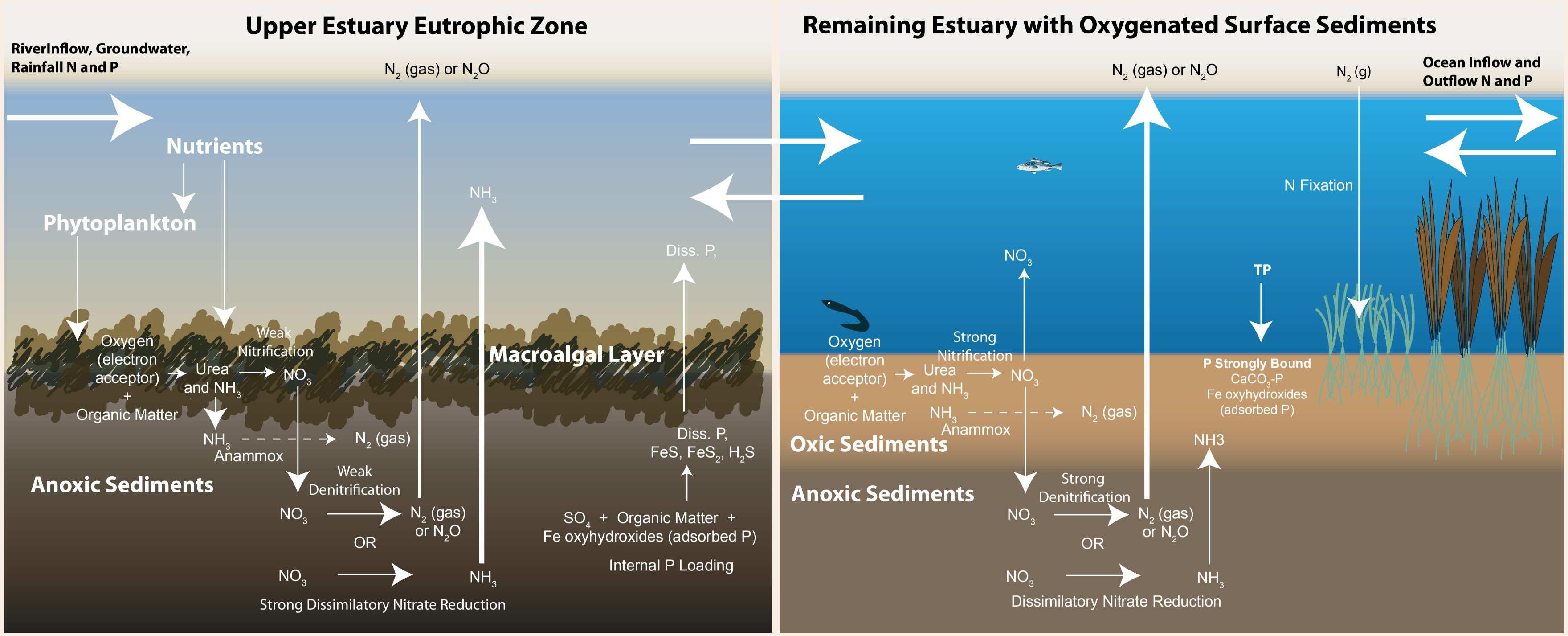


Figure A4. Conceptual diagram of key components of a nutrient model with explanatory notes below.

- **Denitrification**. Amount of denitrifcation is inversely proportional to the amount of nitrate from an oxic zone above the oxygen penetration depth. When nitrate for denitrification is derived from nitrification, the process is called coupled nitrification-denitrification. Nitrification is inhibited when sediments are anoxic, and this can cause a lowering of denitrification efficiencies and relatively more nitrogen may be returned to the water column as ammonium (unless denitrification is coupled to water column nitrate - i.e. oxic conditions are available above the anoxic layer). Denitrification efficiencies become successively lower as carbon loadings move into the mesotrophic, eutrophic and hypertrophic range, and more and more nitrogen is recycled in bioavailable forms (such as ammonium). Denitrification can be enhanced by bioturbation. Seagrasses and other benthic plants and algae may also enhance coupled nitrification-denitrification because they oxygenate the upper sediment layers. However saturating the upper sediment layers with oxygen can also have the reverse effect, and lower denitrification rates during daylight hours. Moreover, if water column nitrogen concentrations are really low, benthic microalgae may inhibit nitrification and denitrification because they compete for nitrate. Denitrifying activity tends to be highest in the summer months coinciding with warmer water temperatures. Denitrification varies inversely with ionic concentration, and is especially high when salinities are <10 ppt. High concentrations of the heavy metals cadmium, copper and zinc in sediment can inhibit denitrification.
- **Dissimilatory Nitrate Reduction**. Alternative NO_3 reduction path competing with denitrification. Takes place under anaerobic conditions. Dominates in C rich environments with low NO_3.
- **Anammox** represents an alternative N removal pathway that circumvents the critical aerobic nitrification phase, typically associated with coupled denitrification.
- **Internal P Loading.** Under persistent anoxic conditions P released from Fe compounds which form insoluble FeS and FeS_2. Diss P is released to porewater and to the water column. The extent of P release from sediment is also affected by pH. Low rates in the pH range from 5-7.
- **Nitrificatiion**. Aerobic conditions, by chemolitho-autrophs who gain energy from oxidation of inorg. N and use CO_2 as only C source. Nitrification is inhibited when sediments are anoxic, and this can cause a lowering of denitrification efficiencies. Under such conditions, relatively less nitrogen may be vented to the atmosphere as N_2 gas, and relatively more nitrogen may be returned to the water column as ammonium.
- **N Fixation**. Nitrogen fixation activity is enhanced in seagrass meadows relative to unvegetated sediments, both in temperate and tropical environments. The availability of organic substrate is a major factor controlling N fixation rates in seagrass sediments. Many studies have shown increases of N fixation by addition of organic compounds, and seasonal and diel variations that are consistent with the role of photosynthetic exudates stimulating N-fixing bacteria.

Table A5. Example of simple mechanistic modelling approach for determining trophic response to nutrient loads.

Inputs:
The model would be driven by inputs of NO_3, NH_4, N_2 and DON, but would likely focus on DIN as the form most likely to be of biological significance (e.g. ELMs model, Valiela et al. 2004). As a consequence, the model would require estimates of conversion rates for DON and N to DIN and would produce an estimate for the delivery of DIN to the estuary on a per unit area basis. This input would include an estimate of nitrogen fixation which can take place in fringing salt marshes, within vegetated and bare estuarine sediments, and in the water column. This uptake of N from the atmosphere by microbial nitrogen fixers in eutrophic estuaries has been shown at times to exceed the nitrogen losses through denitrification (Bowen and Valiela 2001, Rao and Charette 2012, Fulweiler et al. 2007), but further studies are required before the relative contributions can be predicted for all estuarine systems. Recent studies in Narragansett Bay (Fulweiler et al. 2014) provide some preliminary insights in that they showed that in any given year, the variability in denitrification and N_2 fixation was high; in some years N_2 was removed (up to 25%) while in others N_2 was added (up to 38%). However, averaging the results over a 10 year period showed that the N_2 removal and uptake tended to be balanced i.e. zero sediment N_2 flux.

N Concentration in Estuary:
A simple approach (where there is no hydrodynamic model) is sometimes taken where the model distributes the net annual DIN load to the estuary into the net volume of water that passes through the estuary within the span of a year. The model calculates this volume from the water volume at mean high tide, and flushing time of water within the estuary. A more complex approach, would be to include a hydrodynamic model, and potentially a sedimentation model, to improve nutrient concentration estimates both within the water column and sediments.

Transformations: Transformations of N are then accounted for including:

- **Denitrification**. This is calculated on a habitat type basis, including saltmarsh, dense macroalgal beds, unvegetated habitat, and seagrass - worldwide rate of estuarine denitrification 1-80mgN.m^2.d^{-1}, (Cornwall et al. 2014) with a mean of 16 and 20mgN.m^2.d^{-1} respectively for saltmarsh and subtidal unvegetated habitat (Valiela et al. 2004). The water residence times were used to estimate losses due to denitrification using the model given by Nixon et al. (1996) for denitrification: % total nitrogen denitrifed = 20.8 log (Rw) + 22.4 ($r^2 = 0.75$) where Rw is the water residence time in months (i.e. 1d = 0.033mo). For NZ's dominant estuary types (i.e. shallow, intertidal dominated), this would indicate a low denitrification rate which is likely to be true given that denitrification is low in short residence time estuaries because of the short period of time available for transformation processes. Rates are also suppressed to low levels by the presence of macroalgal beds which compete with denitrifiers for NO_3 (Anderson et al. 2003).
- **Loss to the Ocean**. This may be measured, or predicted using simple dilution and tidal outflow parameters, or by using the hydrodynamic/sedimentation component of the model to estimate dilution and losses.
- **Deposition in Vegetated and Unvegetated Sediments**. Some of the land-derived and estuarine N is buried within aggrading sediments of fringing salt marshes, seagrass, macroalgae and unvegetated sediments. Results for NZ estuary habitat based on measured sedimentation rates and sediment N concentrations range from 1- 10mgN.m^2.d^{-1} for low -moderate sedimentation rate areas and up to 600mgN.m^2.d^{-1} for gross eutrophic deposition zones (Regional Council monitoring data - Wriggle database). This compares with 13mgN.m^2.d^{-1} as the estimated N deposition rate measured for the Waquoit (USA) estuarine system (Valiela et al. 2004). This factor is considered the major mechanism for eutrophication symptoms in NZ's dominant estuary type. The proportion of the input nutrients that are bound within the terrestrially derived suspended sediment (i.e. particulate nutrients) is generally around 60-80% of the total terrestrial nutrient load to an estuary (Kroon et al. 2012). Once fine suspended particles (particularly clays, silts and organic matter and bound nutrients) hit saline water in the upper estuary their electric charge causes them to flocculate. The resulting floccule is larger and tends to settle more readily (Xu et al. 2010). Once settled in so-called "deposition zones", which are usually in the upper estuary area (but can also be in the lower estuary if currents are too strong upstream) where the tidal/river flow is weakest, the flocs consolidate further as their water content is forced out by the weight of overlying sediments and become more resistant to erosion. Such sedimentation is encouraged by the presence of vegetation, e.g. saltmarsh, seagrass and macroalgae. Extensive broad scale habitat mapping of NZ estuaries (e.g. Figure 2, and Stevens and Robertson 2012) confirm the presence of such deposition zones in NZ estuaries and that they are commonly located in areas protected from the wind and tidal/river currents. Such protection can be provided by larger scale processes (e.g. distance from channels, location in a sheltered arm), or lesser scale processes (e.g. growth of opportunistic macroalgae on sandy flats facilitating fine mud settlement and promoting more macroalgal growth and muddier sediments). Subsequent physical/chemical/biological processes acting on the sediment/nutrient particles, results in increased bioavailable porewater nutrient concentrations, leading to increased benthic macroalgal growth.
- **Release From Sediments**. Sediment release of N from NZ estuary sediments takes place in all habitats but is focused on saltmarshes, seagrass, and subtidal and intertidal sediments. Release of DIN from saltmarsh sediments was about 5mgN.m^2.d^{-1} in a Cape Cod saltmarsh (White and Howes 1994) and 30mgN.m^2.d^{-1} in shallow subtidal sediments (Valiela et al. 2004).

Plant Uptake and Release. Uptake and release of dissolved nutrients from the water column can occur by phytoplankton, macroalgae and rooted plants. Because this uptake is often balanced by release, many simple models ignore this component (Valiela et al. 2004). However, for the majority of NZ estuaries some measure of biomass production is required if the key primary symptoms of eutrophication are to be adequately represented, and nutrient load/trophic response relationships identified. This may be simply using the model to predict sediment and water column nutrient concentrations and potential eutrophication hot spots (e.g. fine sediment deposition zones) resulting from a gradient of input loads, and then using a proven relationship between location, concentrations and trophic response to estimate the extent of eutrophication for a particular nutrient load.

TOOL 1: APPENDIX 3. SUPPORTING TECHNICAL INFORMATION: ICOLL SUSCEPTIBILITY TO EUTROPHICATION

3.1 NUTRIENT LOADS

NZ ICOLL Data	Table A6 presents physical and nutrient load characteristics, physical and nutrient load susceptibilities, and seagrass growth potential, of 8 NZ ICOLLs (including tidal lagoons, tidal rivers, and tidal river/stream ICOLL types). Although the data are limited, the estimates generally support the available data on current trophic status and seagrass growth in the ICOLL dataset (Table A7).

Table A6. Physical and nutrient load characteristics of 8 NZ ICOLLs and susceptibility to eutrophication and seagrass loss.

ICOLL	Type	Area (km^2)	Tidal Range when open (m)	Volume ($x10^3$ m3)	Low Tide Vol ($x10^3$ m3)	Mean FW inflow m^3/s	N Load (kg/yr)	N Load ($mg/m^2/d$)	ECI days/yr	ECI_{consec} days/yr	ICOLL Flushing Potential	ICOLL Dilution Potential	Physical /Nutrient Susceptibility Rating	Water Level Factor	Water Level Factor	Clarity Factor	Seagrass Potential	Interim N Load Susceptibility Band
Waituna Lagoon	TL	13.59	0.3	12588	8511	6.65	250000	50	200	219	13.15	6.43	High	8.5	Yes	Yes	Yes	D
Lake Onoke	TR	6.65	0.3	20721	18726	172	1741000	717	47	14.6	0.06	1.36	Low	106.0	No	No	No	NA
Te Waihora	TL	198.16	0.3	179138	119690	16	4500000	62	313	91.25	32.40	3.43	Mod	2.2	Yes	No	No	D
Lake Brunton	TL	0.258	0.3	258	180	0.49	15250	162	237	87.6	1.46	7.40	High	38.9	Yes	Yes	Yes	D
Waiau Lagoon	TR	1.01	0.3	2454	2151	30	190000	515	1.5	0.9855	0.00	0.09	Low	3.7	Yes	No	No	NA
Hoopers Inlet	TL	3.75	0.3	3636	2511	0.21	10000	7	292	361.35	198.43	1.44	High	1.4	Yes	Yes	Yes	NA
Grants Road (Tasman)	TR	0.002	0.3	2.6	2	0.013	100	137	219	219	1.39	10.95	Very High	123.0	No	Yes	No	NA
Kakanui Estuary	TR	0.25	0.3	499	424	8	40000	438	146	146	0.29	13.77	High	403.7	No	?	No	NA

Data sourced from NIWA Coastal Explorer database, Wriggle Coastal Management database, and Regional Council monitoring reports. NA=Not Assessed, TL=Tidal Lagoon, TR=Tidal River

Table A7. Predicted susceptibility and actual trophic status and seagrass potential of 6 NZ ICOLLs.

ICOLL	Description	Predicted Susceptibility	Seagrass Potential	Current Trophic State	Current Seagrass Extent
Grants Road	Small tidal creek ICOLL which has a high period of closure.	Very High	Very Low	Very Eutrophic (macroalgae)	Absent
Waituna Lagoon and Hoopers Inlet	Moderate sized tidal lagoon ICOLLs which have very long periods of closure.	High	High	Eutrophic (macroalgae)	Present
Te Waihora	Very large and therefore well diluted, but poorly flushed, with moderate period of closure.	Moderate	Very Low	Eutrophic (phytoplankton)	Absent
Waiau Lagoon, and Lake Onoke	Very well-flushed tidal river ICOLLs, with very short periods of closure.	Low	Very Low	Low/moderate trophic state	Absent or sparse, introduced emergent macrophytes present

Data sourced from Wriggle Coastal Management database, and Regional Council monitoring reports.

NSW ICOLLs Thresholds (Scanes, unpub. 2012)	Scanes (2012) examined 57 ICOLLs in New South Wales, Australia and assessed their condition as described by chlorophyll a, TN and TP as well as the nutrient and sediment loads derived from their catchments. The report classified the ICOLLs (tidal lagoon types with long periods of closure) with regard to condition (reference, moderately disturbed, and highly disturbed) and with regard to their catchment loads (low, medium, high). Limits for "moderate" condition (some eutrophic symptoms but still support healthy seagrass and fish communities) were 25 and 1.56mg.m^{-2}.d^{-1} for N and P respectively, "reference" (pristine) conditions were 7.7 and 0.55mg.m^{-2}.d^{-1} and "high" (algal dominated, turbid systems, seagrass absent or reduced) were 38.5 and 5.5mg.m^{-2}.d^{-1}.
NZ ICOLL Lake Brunton (Robertson and Stevens 2013a)	Lake Brunton, a small shallow NZ ICOLL with a lagoon that opens to the sea more often than Waituna or the Australian ICOLLs above, in 2009 and 2013 had 30-35% of the lagoon area with low density seagrass (*Ruppia*) growth (Robertson and Stevens 2013a) and moderately clear water conditions. However, occasionally when closed for long periods (months), extensive nuisance macroalgal growth and anoxic sediments have been apparent. Nutrient loads have increased significantly in recent years and are currently estimated at ~160 and 5mg.m^{-2}.d^{-1} for N and P respectively. It is expected that this estuary is currently on the threshold of shifting towards a more degraded state with low macrophyte cover.

TOOL 1: APPENDIX 3. SUPPORTING TECHNICAL INFORMATION: ICOLL SUSCEPTIBILITY TO EUTROPHICATION (CONTINUED)

NZ ICOLLs (Wriggle Coastal Management database)	**Shallow NZ ICOLLs** The relationship between nitrogen areal load and trophic response of five shallow NZ ICOLLs, measured as a proportion of available habitat with algal blooms [either macroalgae exceeding 50% cover and sediment surface anoxia (and presence of sulphides) or chlorophyll a exceeding mean of 20mg.m^{-3}] is presented in Figure A5. As expected, the results indicate that tidal river ICOLLs with closure periods of days were relatively insensitive to nutrient loads compared with tidal lagoon ICOLLs with closure periods of months. Although the data set is limited, the findings provide support for Scanes (2012) thresholds for shallow tidal lagoon type ICOLLs with long periods of closure; i.e. a shift to eutrophic conditions at approximately 25mg.m^{-2}.d^{-1} for TN.

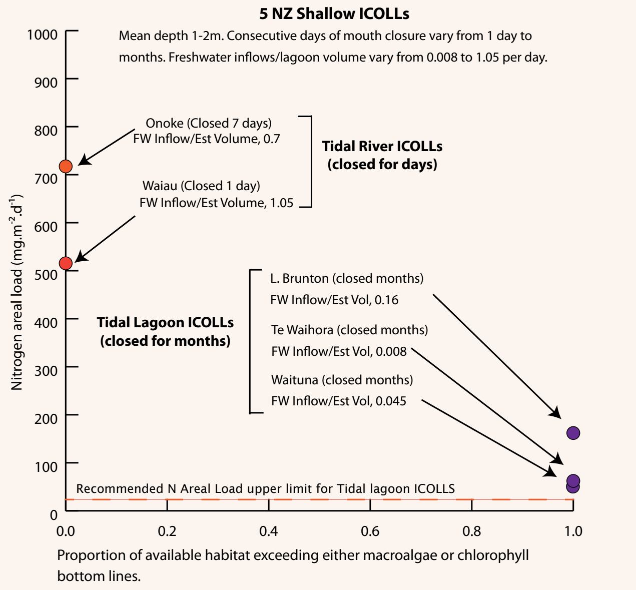


Figure A5. N areal load and trophic response of 5 shallow NZ ICOLLs.

Data sourced from NIWA's Coastal Explorer database, Wriggle Coastal Management database, and Regional Council monitoring reports.

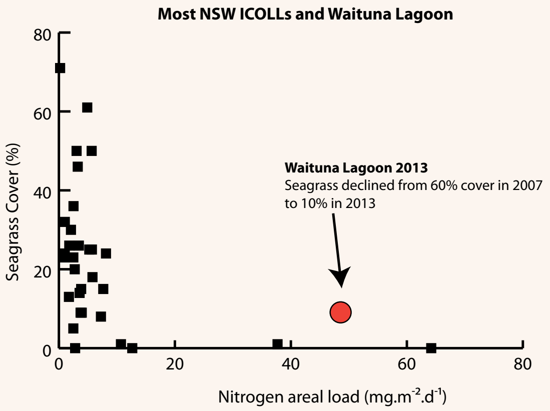


Figure A6. N load and seagrass cover of 31 shallow Australian ICOLLs (usually closed to the sea or mouth choked) and one NZ ICOLL.

Australian ICOLLs (Sanderson & Coade 2010) and Waituna Lagoon NZ	Relationships of seagrass cover and nitrogen loading for 31 shallow Australian lagoons that are usually closed to the sea, or the mouth is almost always choked (Sanderson and Coade 2010), revealed strong effects of nitrogen loading on seagrass cover, with a strong, negative threshold on seagrasses apparent at an effective areal N load of ~10mg.m^{-2}.d^{-1} (Figure A6). Waituna Lagoon, a NZ ICOLL with similar physical characteristics to the Australian lagoons, is currently showing a large reduction in seagrass cover in response to nutrient areal loads of ~50 and 2.9mg.m^{-2}.d^{-1} for N and P respectively. In 2007, 60% of Waituna Lagoon area had some seagrass growth (and 30% with high density seagrass) (Robertson and Stevens 2007a), while in 2013 extensive transect studies indicated the presence of seagrass at ~10% of estuary area. Such a decline coincided with extensive macroalgal growth and anoxic sediment conditions (e.g. Sutherland et al. 2013).

3.2 NUTRIENT CONCENTRATIONS (WATER COLUMN)

Maryland Coastal Lagoons	Nutrient thresholds to protect seagrass in Maryland coastal lagoons were set at median values for total nitrogen <650ugN/l and total phosphorus <370ugP/l (Wazniak et al. 2007).
NZ ICOLLs: Schallenberg and Schallenberg 2012; Norton et al. 2014	In a survey of NZ ICOLLs sampled in late summer, macrophyte cover was inhibited with increasing water column TN concentration while the chlorophyll-a concentration in the water column increased with TN concentration. There was a threshold TN concentration of about 1000ug/l, below which ICOLLs were dominated by aquatic plants, and above which lakes were dominated by phytoplankton. Using the same dataset, Drake et al. (2010) found that a TN concentration of 800mg/m^3 corresponded to <30% cover of macrophytes.
Overseas Shallow Lakes (operate similarly to ICOLLs)	Overseas studies have found a loss of macrophyte cover in shallow lakes with in-lake TN concentrations of between 1000-2000mg/m^3 and TP was moderately high (see enclosure experiments by González-Sagrario et al. (2005), and regression analysis of 44 Danish lakes in Jeppesen et al. (2007)). It was rare for these lakes to have greater than 50% macrophyte cover when the TN concentration was >1000mg/m^3 (Jeppesen et al. 2007, Kelly et al. 2013).
Danish Estuaries	Growth saturating concentrations of nitrate and ammonia for *Ulva*, 0.18-0.09mg/l respectively (Pedersen and Borum, 1997).

TOOL 1: APPENDIX 4. SUPPORTING TECHNICAL INFORMATION: SIDE SUSCEPTIBILITY TO EUTROPHICATION

4.1 NUTRIENT LOADS

NZ Data

THE FOLLOWING INFORMATION HAS BEEN PROVIDED BY BEN ROBERTSON AS PART OF PRELIMINARY OTAGO UNIVERSITY PHD RESEARCH OUTPUTS AND MAY NOT BE REPRODUCED WITHOUT PERMISSION.

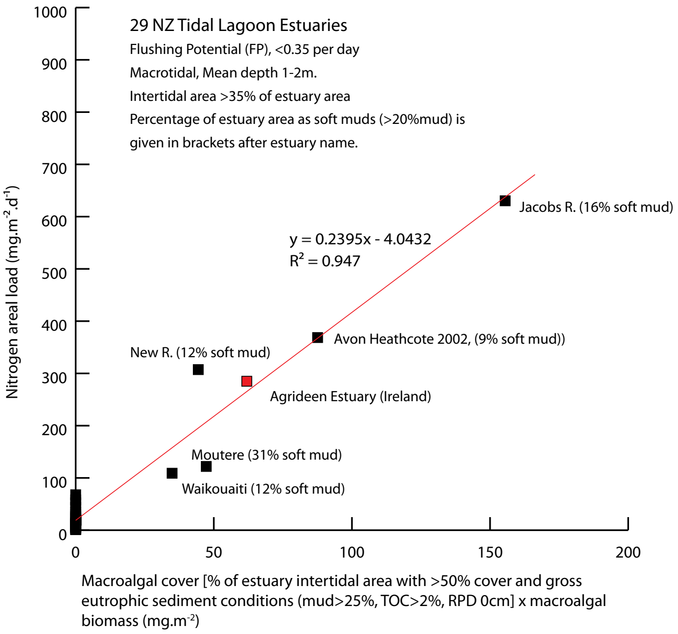
Table A8 presents physical and nutrient load characteristics, and physical and nutrient load susceptibilities, of 29 NZ shallow intertidal dominated estuaries (including tidal lagoons, tidal rivers and tidal river delta types). Although the data are limited, the estimates generally support the available data on current trophic status in the data set.

Table A8. Physical and nutrient load characteristics of 29 NZ shallow intertidal dominated estuaries and susceptibility to eutrophication.

Shallow Intertidal Dominated Estuaries	Type	Area (km^2)	Tidal Range (m)	Volume (x10^3 m3)	Mean depth (m)	Mean FW inflow m^3/s	N Areal Load (mg/m^2/d)	Dilution Potential (ASSETS)		Flushing Potential (ASSETS)		Export Potential (ASSETS)	N Load Influence (ASSETS approach)		Overall Human Influence (ASSETS)	N Load susceptibility (from SIDES load/response curve)	Combined N Load and Physical Plus Mud Susceptibility	Current Eutrophication Symptoms
Bluff Harbour	TL	54.58	2.22	121989	2.24	3.4	1.0	2.32E-10	Mod	0.0024	Mod	Mod	0.00	Low	Low	Low	Low	Low
Blueskin Bay	TL	6.23	1.63	7559	1.21	2.9	4.9	3.75E-09	Low	0.0331	High	Mod	0.03	Low	Low	Low	Low	Low
Porirua Harbour	TL	8.09	1.05	9679	1.3	8.8	30.5	2.93E-09	Low	0.0783	High	Mod	0.14	Low	Low	Mod	Mod	Mod
Nelson Haven	TL	12.63	3.64	37895	3	5.9	6.5	7.47E-10	Mod	0.0136	High	High	0.01	Low	Low	Low	Low	Low
Waikawa Harbour	TL	6.42	2.01	9835	1.5	9.5	58.0	2.88E-09	Low	0.0831	High	Mod	0.20	Low	Low	Mod	Mod	Low-Mod
Haldane Estuary	TL	1.89	2.04	2337	1.2	2.6	52.4	1.21E-08	Low	0.0973	High	Mod	0.19	Low	Low	Mod	Mod	Low
New River Estuary	TL	46	2.21	60269	1.8	145	265.4	4.70E-10	Mod	0.2082	High	High	0.47	Mod	Mod	V High	High	High
Jacobs River Estuary	TL	7.29	2.26	14697	2.2	54.1	630.3	1.93E-09	Low	0.3182	High	Mod	0.69	High	Mod	V High	V. High	V. High
Avon-Heathcote River 2002	TL	7.47	1.79	13948	1.9	4.5	368.7	2.03E-09	Low	0.0279	High	Mod	0.61	High	Mod	V High	V. High	V. High
Ohiwa Harbour	TL	26.84	1.7	44190	1.6	9.5	12.9	6.41E-10	Mod	0.0185	High	High	0.06	Low	Low	Mod	Mod	Low
Kaipara (Otamatea Arm) 2003	TL	17	2.4	85000	3	3.0	14.5	3.33E-10	Mod	0.003	Mod	Mod	0.03	Low	Low	Mod	Mod	Mod
Waimea Inlet	TL	29.33	3.66	99818	2	46	23.4	2.84E-10	Mod	0.0403	High	High	0.04	Low	Low	Mod	Mod	Mod
Moutere Inlet	TL	6.85	3.63	18974	1	6.8	122.0	1.49E-09	Low	0.0311	High	Mod	0.19	Low	Low	High	High	High
Whanganui Inlet	TL	25.08	3.11	29669	1.2	6.1	1.6	9.54E-10	Mod	0.0179	High	High	0.00	Low	Low	Low	Low	Low
Motupipi River	TL	1.21	3.61	2989	1	2.2	34.0	9.47E-09	Low	0.0643	High	Mod	0.07	Low	Low	Mod	Mod	Mod
Avon-Heathcote River 2012	TL	7.47	1.79	13948	2	4.5	19.1	2.03E-09	Low	0.0279	High	Mod	0.07	Low	Low	Mod	Mod	Mod
Kaiteriteri Estuary	TL	0.17	3.59	388	0.8	0.2	11.1	7.30E-08	Low	0.0356	High	Mod	0.03	Low	Low	Mod	Mod	Low
Wainui Inlet	TL	1.83	3.57	4444	1.5	2.1	25.8	6.37E-09	Low	0.0403	High	Mod	0.06	Low	Low	Mod	Mod	Low
Otuwhero Inlet	TL	0.89	3.58	2479	0.8	2.9	43.5	1.14E-08	Low	0.0998	High	Mod	0.09	Low	Low	Mod	Mod	Low
Ligar Bay	TL	0.36	3.59	1280	0.5	0.2	4.6	2.21E-08	Low	0.0135	High	Mod	0.01	Low	Low	Low	Low	Low
Parapara Inlet	TL	1.83	3.65	3900	1.8	6.5	22.2	7.26E-09	Low	0.1444	High	Mod	0.05	Low	Low	Mod	Mod	Low
Waikato Estuary	TL	0.21	3.67	378	0.5	0.2	13.3	7.48E-08	Low	0.0465	High	Mod	0.03	Low	Low	Mod	Mod	Low
Pakawau Inlet	TL	0.74	3.68	1366	1.2	0.4	12.2	2.07E-08	Low	0.0249	High	Mod	0.03	Low	Low	Mod	Mod	Low
Port Puponga	TL	0.33	3.7	994	1.5	0.2	10.0	2.85E-08	Low	0.0195	High	Mod	0.02	Low	Low	Low	Low	Low
Delaware Estuary	TL	3.1	3.52	6270	2	4.3	8.8	4.52E-09	Low	0.0592	High	Mod	0.02	Low	Low	Low	Low	Low
Purakanui Inlet	TL	1.13	1.63	1295	1.1	0.2	1.9	2.19E-08	Low	0.0162	High	Mod	0.01	Low	Low	Low	Low	Low
Freshwater Estuary Delta	TRD	8.12	2.2	16240	2	8.0	6.9	1.74E-09	Low	0.0426	High	Mod	0.02	Low	Low	Low	Low	Low
Waikouaiti River	TR	1.27	1.62	2181	1.71	3.0	107.7	1.30E-08	Low	0.1189	High	Mod	0.34	Mod	Mod	High	High	V. High
Havelock Delta Estuary	TRD	16	2.2	24000	3	47.0	67.8	1.18E-09	Low	0.1692	Mod	Low	0.93	V. High	Mod	High	High	Moderate

Data sourced from NIWA Coastal Explorer database, Wriggle Coastal Management database, and Regional Council monitoring reports. TL=Tidal Lagoon, TR=Tidal River, TRD=Tidal River + Delta

TOOL 1: APPENDIX 4. SUPPORTING TECHNICAL INFORMATION: SIDE SUSCEPTIBILITY TO EUTROPHICATION (CONTINUED)

NZ Shallow Intertidal Dominated Estuaries (Wriggle Coastal Management database)	**THE FOLLOWING INFORMATION HAS BEEN PROVIDED BY BEN ROBERTSON AS PART OF PRELIMINARY OTAGO UNIVERSITY PHD RESEARCH OUTPUTS AND MAY NOT BE REPRODUCED WITHOUT PERMISSION.** Robertson (in prep) examined an extensive data set of 29 shallow NZ tidal lagoon estuaries (permanently open but predominantly South Island and Lower North Island estuaries) and demonstrated a highly significant relationship between the N areal load and macroalgal expression* (i.e. presence of gross nuisance zones with high macroalgal biomass and accompanying sediment anoxia and elvated mud content) ($R^2 = 0.958$) (Figure A7). These findings indicate a preliminary nitrogen areal loading threshold for the appearance of gross nuisance macroalgal conditions at approximately 100mgN.m^{-2}.d^{-1}. The threshold for more extensive appearance of gross nuisance conditions was ~200mgN.m^{-2}.d^{-1}. The findings also strongly identified flushing potential as a major moderator of impact, and the presence of soft mud as a covariable with gross eutrophic conditions. However, given the following facts: • that the relationships were derived from predominantly South Island and lower North Island estuaries (i.e. non-mangrove estuaries), • that the dominant location for gross nuisance macroalgal conditions in these estuaries was generally above mean sea level (i.e. midway between low and high tide levels) and, • that mangroves grow down to mean sea level, then it seems appropriate to limit the use of the N areal load thresholds to estuaries that do not naturally grow mangroves (i.e. South Island and Lower North Island estuaries). Such a proviso acknowledges that mangroves, with their high mud retention capacity, and strong ability to oxygenate sediments, may repress the response of macroalgae to nitrogen loads. For similar reasons, it is also noted that the relationship should not be used where other saltmarsh species grow down to mean sea level (e.g. *Spartina* sp. in European and USA estuaries).  **Figure A7. N areal load and "macroalgal expression".** Data sourced from Wriggle Coastal Management database, Regional Council monitoring reports, CLUES model and NIWA Coastal Explorer database. *** Macroalgal Expression** = [macroalgal biomass in gross nuisance zones in mg.m^{-2}] x [proportion of intertidal habitat with gross nuisance macroalgal conditions (i.e. macroalgae exceeding 50% cover, mud content >25%, and aRPD 0cm)]
USA Shallow estuaries (Fox et al. 2008)	Recent overseas studies have shown that estimates of nutrient loading that include all possible sources as well as physical removal (flushing) are accurate and generalisable predictors of macroalgal biomass (Sutula 2011). In one of the best examples of this approach, Fox et al. (2008) compared three sub-estuaries of Waquoit Bay, Massachusetts (maximum water depth of <3 m and an average water depth of approximately 1.5m, tidal range 0.6m), with different nitrogen loads and found the magnitude of macroalgal standing stock was predicted by total nitrogen load over a six-year period. These findings showed a clear shift to high macroalgal biomass (>800g.m^{-2} wet weight) at N areal loads above approximately 100mgN.m^{-2}.d^{-1}.

TOOL 1: APPENDIX 4. SUPPORTING TECHNICAL INFORMATION: SIDE SUSCEPTIBILITY TO EUTROPHICATION (CONTINUED)

NZ Shallow Intertidal Dominated Estuaries and Seagrass Cover

THE FOLLOWING INFORMATION HAS BEEN PROVIDED BY BEN ROBERTSON AS PART OF PRELIMINARY OTAGO UNIVERSITY PHD RESEARCH OUTPUTS AND MAY NOT BE REPRODUCED WITHOUT PERMISSION.

Seagrass (e.g. *Zostera muelleri)* in shallow tidal lagoon estuaries plays a vital role in NZ estuarine ecology and is well-documented as a keystone species (e.g. Barbier et al. 2011, Schallenberg and Tyrrell 2006). They attenuate and assimilate nutrients and sediment, and provide high value habitat for a wide range of biota. The presence of extensive submerged aquatic vegetation (SAV) beds in good condition in shallow tidal lagoon estuaries generally indicates low/moderate nutrient and sediment inputs, whereas die-off and loss of SAV is generally indicative of excessive nutrient and sediment inputs and eutrophic conditions. Where nutrient loads and sediment are excessive, dense beds of opportunistic macroalgae smother seagrasses and cause toxicity from high ammonium concentrations remineralised from senescent macroalgal canopies (van Katwijk et al. 1997), anoxia around the seagrass meristem (Greve et al. 2003), and release of toxic sulphides which may inhibit photosynthesis (Goodman et al. 1995). However, because of their short residence time, shallow NZ tidal lagoon estuaries generally only experience extensive seagrass loss in upper estuary areas of developed catchments where flocculation and nutrient and sediment deposition is encouraged. In the middle and lower estuary, where the marine influence results in sandier sediments and clearer waters, seagrass is more common.

Figure A8 shows that significant seagrass cover in 29 shallow NZ tidal lagoon estuaries was only present where the intertidal area covered in soft muds (>25% sediment mud content) was <15% and if nutrient loads were less than approximately 100mgN.m^{-2}.d^{-1}. In New England estuarine systems (deeper and with longer residence times than most NZ estuaries) eelgrass loss began to occur at N loads above 18.2mgN.m^{-2}.d^{-1} and eelgrass disappeared at 36.5mgN.m^{-2}.d^{-1} (Latimer and Rego 2010).

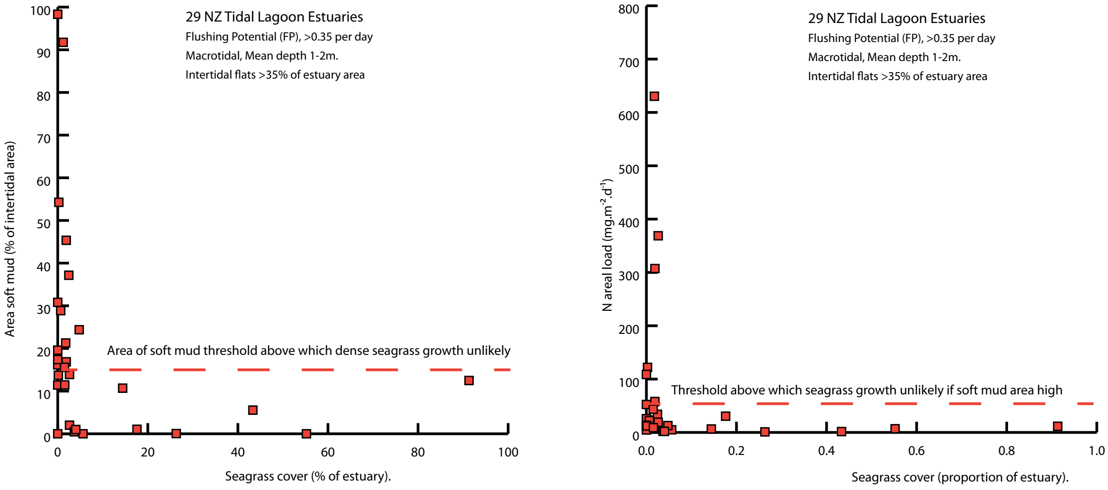


Figure A8. Relationship between seagrass cover (%) and area of soft mud (left), and seagrass cover and N areal load (right) in 29 shallow NZ tidal lagoon estuaries.

Data sourced from Wriggle Coastal Management database, and Regional Council monitoring reports.

4.2 NUTRIENT CONCENTRATIONS (WATER COLUMN) (generalised guidelines for multiple estuary types)

European Estuary Guidelines. OSPAR (2008)	Dissolved Inorganic Nitrogen (N) High <280 ug/l, Good 280-420 ug/l, Moderate 420 -630 ug/l, Poor >630 ug/l.
ASSETS Approach Bricker et al. (1999)	Total Nitrogen. Maximum dissolved surface concentration: High (≥1000 ug/l), Medium (100-1000 ug/l), Low (0-100 ug/l)
ANZECC (2000) Guidelines	S.E. Australia default trigger values used for NZ (ug/l): DIN >30 TN 300 DRP 5 TP 30

TOOL 1: APPENDIX 5. SUPPORTING TECHNICAL INFORMATION: SSRTRE SUSCEPTIBILITY TO EUTROPHICATION

5.1 NUTRIENT LOADS

NZ Data

Table A9 presents physical and nutrient load characteristics, physical and nutrient load susceptibilities, and the current expression of eutrophication symptoms (based on Regional Council monitoring data and expert opinion) of 17 NZ shallow short residence time tidal river and tidal river-lagoon estuaries. Although the data are limited, the estimates of physical susceptibility to nutrient loads using the recommended NZ approach generally support the available data on current trophic status in the data set.

Figure A9 provides data for 16 NZ SSRTRE estuaries which supports the typical low macroalgal biomass and gross nuisance macroalgal zones in these estuaries.

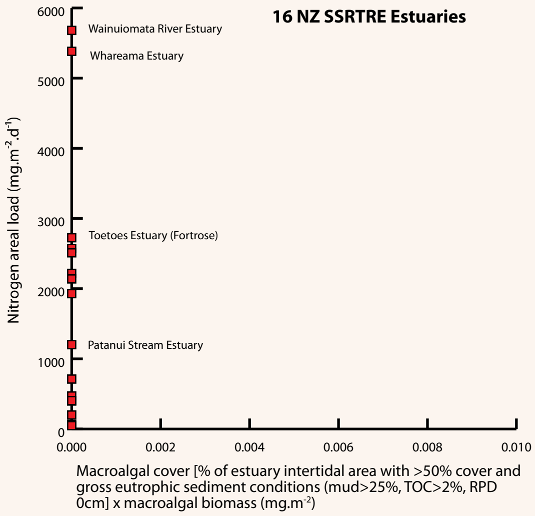


Figure A9. Relationship between N areal load and "macroalgal expression" in 16 shallow NZ SSRTRE estuaries. Data sourced from Wriggle Coastal Management database, and Regional Council reports.

Table A9. Physical and nutrient load characteristics of 17 NZ shallow short residence time tidal river estuaries and susceptibility to eutrophication (coloured cells denote estuary with high risk habitat).

Short Residence Time, Subtidal Dominated Tidal River Estuaries	Area (km^2)	Tidal Range (m)	Volume (x10 3 m3)	Mean depth (m)	Mean FW inflow m3/s	N Areal Load ($mg/m^2/d$)	Dilution Potential (ASSETS)		Flushing Potential (ASSETS)		Export Potential (ASSETS)	N Load Influence (ASSETS approach)		Overall Human Influence (ASSETS)	N Load Susceptibility. Low risk estuaries applied 2000 mgN.m2.d threshold and for High Risk estuaries ASSETS approach.	Current Eutrophication Symptoms (Expert Opinion)
Wanganui Estuary	3.22	2.62	7684	2.4	388.9	2572	3.69E-09	Low	4.37	High	Mod	0.83	V. High	High	Mod	Low
Wharamea Estuary	0.12	1.34	277	2.3	20.4	5382	1.02E-07	Low	6.37	High	Mod	0.95	V. High	High	Mod	Low
Hutt Estuary	0.30	1.1	600	2	24.8	2511	4.72E-08	Low	3.57	High	Mod	0.92	V. High	High	Mod	High
Kaikorai Estuary	0.64	1.68	2100	2.5	1.3	66	1.35E-08	Low	0.05	High	Mod	0.16	Low	Low	Low	Low
Toetoes Harbour	4.75	2.14	11872	2.5	205.2	2726	2.39E-09	Low	1.49	High	Mod	0.86	V. High	High	Mod	Mod
Ruataniwha Inlet	6.61	3.66	15029	1.5	108.1	200	1.88E-09	Low	0.62	High	Mod	0.21	Mod	Mod	Low	Low
Waikanae River	0.33	1.81	618	1.5	0.8	471	4.58E-08	Low	0.12	High	Mod	0.57	High	Mod	Low	Low
Porangahau River	2.26	1.37	1667	1	31.8	399	1.70E-08	Low	1.65	High	Mod	0.59	High	Mod	Low	Low
Castlepoint	0.29	1.35	443	0.5	0.4	48	6.39E-08	Low	0.08	High	Mod	0.15	Low	Low	Low	Low
Motuwaireka Stream	0.05	1.34	112	1	1.2	712	2.53E-07	Low	0.95	High	Mod	0.73	High	Mod	Low	Low
Patanui Stream	0.03	1.34	61	2.2	1.7	1202	4.65E-07	Low	2.43	High	Mod	0.82	V. High	High	Low	Low
Pahaoa River	0.16	1.31	371	2.3	25.9	2218	7.64E-08	Low	6.03	High	Mod	0.89	V. High	High	Mod	Low
Oterei River	0.07	1.30	72	1	2.5	405	3.94E-07	Low	2.98	High	Mod	0.61	High	Mod	Low	Low
Awhea River	0.06	1.30	57	1	6.1	1929	4.98E-07	Low	9.33	High	Mod	0.88	V. High	High	Low	Low
Wainuiomata River	0.04	1.10	41	1	8.1	5680	6.99E-07	Low	17.22	High	Mod	0.96	V. High	High	Mod	Low
Awatere River	0.09	1.35	187	2.2	52.9	24952	1.51E-07	Low	24.43	High	Mod	0.99	V. High	High	Mod	Low
Awarua River	0.12	1.98	460	4	11.0	2139	2.89E-06	Low	2.07	High	Mod	0.84	V. High	High	Mod	Low

Data sourced from NIWA Coastal Explorer database, Wriggle Coastal Management database, and Regional Council monitoring reports.

TOOL 1: APPENDIX 6. SUPPORTING TECHNICAL INFORMATION: DSDE SUSCEPTIBILITY TO EUTROPHICATION

6.1 NUTRIENT LOADS

NZ Data	Table A10 presents physical and nutrient load characteristics, physical and nutrient load susceptibilities, and the current expression of eutrophication symptoms (based on Regional Council monitoring data and expert opinion) of 20 NZ deeper, long residence time, subtidal dominated estuaries. Although the data are limited, the estimates of physical susceptibility to nutrient loads using the recommended NZ approach generally support the available data and/or expert opinion on current trophic status in the data set.

Table A10. Physical and nutrient load characteristics of 20 NZ Deeper and Predominantly Subtidal Coastal Embayments, Tidal Lagoons and Fiord Estuaries and their estimated susceptibility to eutrophication.

Deeper, Subtidal Dominated Estuaries	Area (km^2)	Tidal Range (m)	Volume (x10 3 m3)	Mean depth (m)	Mean FW inflow m3/s	N Areal Load (mg/m^2/d)	Dilution Potential (ASSETS)		Flushing Potential (ASSETS)		Export Potential (ASSETS)	N Load Influence (ASSETS approach)		Combined Physical and Nutrient Susceptibility (=ASSETS OHI)	Current Eutrophication Symptoms (Expert Opinion)
Firth of Thames System	729.08	2.86	6865963	9.4	186	23	4.12E-12	High	0.00234	Mod	High	0.48*	Mod-Low	Low	Mod
Wellington Harbour	85.42	1.03	1369490	16	41	10	2.07E-11	High	0.00261	Mod	High	Not calculated due to the general absence of data required to determine ocean influence e.g. ocean N load or N concentration. It is envisaged that CLUES estuaries will be able to produce such estimates in the near future.			Low
Otago Harbour	47.91	1.63	184774	3.9	4	2 ??	1.53E-10	Mod	0.00171	Mod	Mod				Mod
Preservation Inlet	93.73	1.94	7298730	77.9	77	7	3.56E-09	Low	0.00091	Mod	Low				Low
Chalky Inlet	109.27	1.91	12729612	116.5	67	6	3.05E-09	Low	0.00045	Mod	Low				Low
Breaksea/Dusky Sound	283.60	1.82	30389042	107.2	273	8	1.18E-09	Low	0.00078	Mod	Low				Low
Coal River	3.21	1.83	44113	13.7	14	49	1.04E-07	Low	0.02651	High	Mod				Low
Dagg Sound	15.51	1.84	778194	50.2	17	19	2.15E-08	Low	0.00194	Mod	Low				Low
Thompson/Doubtful Sound	137.34	1.86	18978271	138.2	239	46	2.43E-09	Low	0.00109	Mod	Low				Low
Nancy Sound	14.51	1.87	1440801	99.3	18	18	2.30E-08	Low	0.00110	Mod	Low				Low
Charles Sound	16.44	1.88	990185	60.2	71	46	2.03E-08	Low	0.00615	Mod	Low				Low
Caswell Sound	17.65	1.89	2491219	141.1	72	44	1.89E-08	Low	0.00250	Mod	Low				Low
Two Thumb Bay	1.22	1.89	8436	6.9	7	119	2.73E-07	Low	0.07059	High	Mod				Low
Looking Glass Bay	1.43	1.89	17270	12.1	3	41	2.34E-07	Low	0.01352	High	Mod				Low
George Sound	30.96	1.91	3304945	106.7	63	34	1.08E-08	Low	0.00164	Mod	Low				Low
Catseye Bay	0.86	1.91	5013	5.9	7	212	3.89E-07	Low	0.11986	High	Mod				Low
Bligh Sound	21.08	1.91	1462616	69.4	46	36	1.58E-08	Low	0.00272	Mod	Low				Low
Sutherland Sound	10.84	1.92	114358	10.5	43	54	3.08E-08	Low	0.03215	High	Mod				Low
Poison Bay	8.40	1.93	321673	38.3	14	38	3.97E-08	Low	0.00371	Mod	Low				Low
Milford Sound	28.40	1.94	3579420	126.0	135	54	1.17E-08	Low	0.00326	Mod	Low				Low

Note: Data sourced from NIWA Coastal Explorer database, Wriggle Coastal Management database, and Regional Council monitoring reports. Fiords corrected for stratification assumed 3m deep stratified layer as the volume available for dilution.

* Calculated using data on nutrient concentrations and salinity from the Firth of Thames provided by John Zeldis.

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