Drivers of Estuary Ecological Health and Water Quality in the Southland Region

Prepared for DairyNZ and Environment Southland

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Executive summary

Environment Southland intends taking an “ecological condition gradient” approach to determining catchment nutrient and sediment load limits that are required to achieve estuarine objectives. This involves identifying a number of estuarine environments that lie along a gradient of very healthy to very degraded, and then developing a matching gradient of sediment and nutrient loadings. The idea is that it will be possible to move any given estuary to a new location on the continuum (e.g., closer to the “healthy” end) by reducing the loads according to the matching contaminant continuum. This may be achievable if there is a causative relationship between the contaminant loading and the indicators of ecological condition (as opposed to a non-causative correlation), and there is no hysteresis in the system response to a reduction in contaminant loading.

As a first step in developing the ecological condition gradient approach, DairyNZ and Environment Southland contracted NIWA to (1) assess the ecological health of four Southland estuaries (Jacobs River Estuary, New River Estuary, Waikawa and Toetoes) using existing monitoring data, and (2) review the main drivers of estuary ecological health and water quality in the region. These drivers are nutrients and fine sediments. The results of the first task are reported in a companion report. The results of the second task are reported herein.

We review the way nutrients and fine sediments cause adverse effects in estuaries, and then review the drivers.

Nutrients

Snelder et al. (2014) found an approximate inverse relationship between total-nitrogen loading from freshwater and overall condition grade for estuary nutrient enrichment. Shallow tidal lagoons were found to have a higher sensitivity to nutrient inputs than shallow tidal rivers, which is consistent with the fact that shallow tidal lagoons are less well flushed than tidal rivers. Snelder et al.’s result supports the contention that land-side total nitrogen loading is at least one driver of estuary trophic state in Southland.

Snelder et al. (2014) found that total nitrogen and nitrate are increasing in freshwater reaches where water quality is already currently poor (as indicated by a 6-category classification of water quality). The four estuaries that are the subject of the ecological health assessment (New River Estuary, Jacobs River Estuary, Waikawa and Toetoes) in the companion report each drain a catchment with poor freshwater water quality. If we assume that Snelder et al.’s inverse relationship between total-nitrogen loading from freshwater and overall condition grade for estuary nutrient enrichment is causative, then we can expect that the trophic state of estuaries will degrade in the future if freshwater nitrogen loads do continue to increase. That may be manifest by more primary and/or secondary symptoms of eutrophication.

Snelder and Fraser (2013) assessed the environmental consequences of the future nutrient runoffs predicted by Palliser and Elliott (2013). Only a few estuaries were predicted to be in an acceptable trophic state within 30 years. Snelder and Legard (2014) looked at how nutrient loads in eight large Southland catchments could be changed by on-farm mitigation measures. They concluded that gains in the future from on-farm mitigations could be quickly eroded by ongoing conversion of sheep and beef to dairy farms and production increases on dairy farms.

Refinement of the predictions of future trophic state and development of the ecological condition gradient for use in limit setting will require, at least, accounting for the characteristic residence time

of land-origin nitrogen in the estuary system, the seasonality of nutrient supply and algal growth potential, and the contribution of internal nutrient sources to primary production.

Process-based understanding of the physical characteristics and nutrient dynamics of Southland estuaries could provide a more robust and nuanced method for setting limits than an ecological condition gradient approach that is based only on correlation relationships (as opposed to causative relationships). A key issue regarding limit-setting is the extent to which, if any, Southland estuaries might simply "reverse" condition following any reduction in land-side nutrient loading, as opposed to following a path that constitutes a hysteresis loop.

Tools that will improve predictions and assist with limit setting are available or in development, and these include the CLUES–Estuaries tool for predicting estuarine "potential" nutrient concentrations under different catchment landuses, a macroalgae growth model being developed by NIWA, and an "Estuarine Trophic Index" currently being developed under an Envirolink grant.

Virtually nothing is known about restoration trajectories that might be followed by New Zealand estuaries following a reduction in land-side nutrient inputs. At the time of writing, a 6-year research programme has been proposed to MBIE by a consortium of researchers for consideration for funding that is designed to address that knowledge gap.

Sediments

Wriggle (and their predecessors) document and discuss a wide range of adverse effects of various severity due to fine sediments in Waikawa, Toetoes, Jacobs River Estuary and New River Estuary, and presume the source of the problematic fine sediments is the catchment.

Wriggle's presumption is most likely to be correct, although there may be complicating factors. For instance, in addition to new inputs of fine catchment sediment, changes in the dynamics of the estuary could cause changes in the internal redistribution of "pre-existing" sediments that result in an increase (or decrease) in the accumulation of fine sediment at any particular site.

Snelder et al. (2014), in an analysis that mirrored the one done for nutrients, explored the relationship between the estuary condition grade for sedimentation and freshwater annual loads of suspended sediment. They could not find a clear relationship between the two, which they surmised might be because the fate of sediments in estuaries is complex. They also did not have confidence in the estimates of the suspended-sediment loads, which were created by a simple regression model. Even if there were a stronger relationship, a deeper understanding of processes would still be required to demonstrate causation rather than just correlation, and from there to predict trends.

A process-based catchment sediment model is required to provide information on sediment loads and past trends in loads to the four study estuaries. The SedNetNZ catchment sediment model is probably the best of the process-based catchment-scale models available at present. Combined with an estuary sediment transport model that explains dispersal, accumulation and flushing of fine sediment, the loads will improve the understanding of drivers of estuary sediment health, which is currently rudimentary, and will assist with development of the ecological condition gradient.

Predictions by a catchment sediment model of future trends in sediment loads will assist management in designing intervention.

1 Introduction

Environment Southland (ES) intends setting catchment sediment and nutrient load limits to achieve environmental objectives in each of four Freshwater Management Units. The FMUs are:

- Mataura – includes Toetoes, Waituna, Waikawa, Haldane, Lake Brunton, the reservoir, Lake Vincent and their respective catchments.
- Aparima – Jacobs River Estuary, Waimatuku and their respective catchments.
- Oreti – New River Estuary and its catchment including Waihopai.
- Waiau – Te Waewae (Waiau) Lagoon and its catchment.

Each FMU encompasses an entire catchment and estuarine receiving waters.

ES intends taking an "ecological condition gradient" approach to determining the catchment nutrient and sediment load limits that are required to achieve estuarine objectives. In essence, this involves identifying a number of estuarine environments that lie along a continuum, or gradient, of very healthy to very degraded (as indicated by a number of attributes, for example, macroalgae cover), and then developing a matching gradient of contaminant loadings (sediments and nutrients). The idea is that it will be possible to move any given estuary to a new location on the continuum (e.g., closer to the "healthy" end) by reducing the loads according to the matching contaminant continuum. This may be achievable if there is a causative relationship between the contaminant loading and the indicators of ecological condition (as opposed to a non-causative correlation), and there is no hysteresis in the system response to a reduction in contaminant loading. The ecological condition gradient is intended by Environment Southland to support the limit-setting process: stakeholders will be asked, in the collaborative process, where they want estuaries to lie on the continuum, and load limits will be set accordingly.

Figure 1-1, which plots purely fictional relationships between estuary ecological condition (1 = good condition, 3 = poor condition) and the two main drivers of ecological condition in the Southland region (nutrients and fine sediments), summarises the concept of the ecological condition gradient.

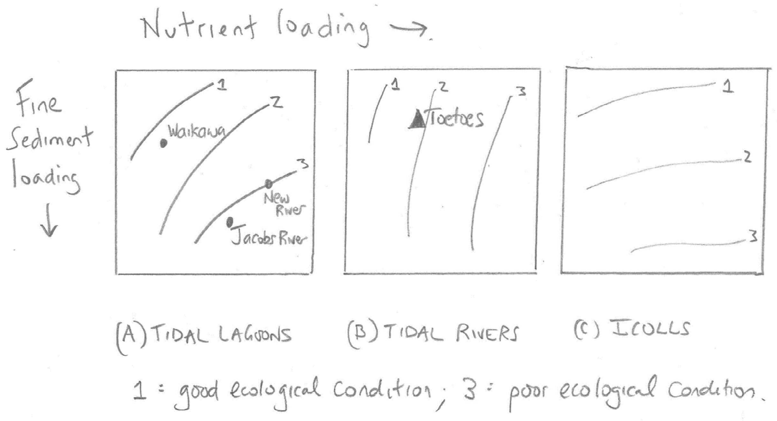

Figure 1-1: Relationships between estuary ecological condition (1 = good condition, 3 = poor condition) and the two main drivers of ecological condition in the Southland region (nutrients and fine sediments). The relationships shown here are purely fictional.

- At any particular nutrient loading, ecological condition deteriorates with an increase in fine-sediment loading.
- Likewise, at any particular fine-sediment loading, ecological condition deteriorates with an increase in nutrient loading.
- The higher the nutrient loading the faster the decrease in condition that is associated with an increase in fine sediment.
- Likewise, the higher the fine-sediment loading the faster the decrease in condition that is associated with an increase in nutrients.
- The relationships between drivers and condition vary by estuary type, reflecting the way nutrients and sediments are "assimilated" by various estuary processes.

As a first step in developing the ecological condition gradient approach, DairyNZ and Environment Southland contracted NIWA to:

1. Assess the ecological health of four Southland estuaries using existing monitoring data. The data belong to Environment Southland, and are publically available on Environment Southland's website at http://www.es.govt.nz/environment/coast/estuaries/estuarine-reports/. The four estuaries to be assessed are New River Estuary, Jacobs River Estuary, Waikawa and Toetoes.
2. Review the main drivers (sediments and nutrients) of estuary ecological health and water quality in the region.

The first task will help Environment Southland locate the estuaries on the panels shown in Figure 1-1. The second task will help confirm the relationships between nutrient and sediment loadings and estuary ecological condition.

1.1 This report

The results of the first task are reported in a companion report.

The results of the second task are reported herein.

2 Nutrients

2.1 Background

Nitrogen and phosphorus delivered in freshwater runoff can add to any ocean sources and cause eutrophication of estuarine and coastal habitats.

Excessive levels of nitrogen and phosphorus fuel the growth of rapidly reproducing algal species such as phytoplankton and macroalgae. Macroalgae, in particular, can smother substrates, animals and other plants, including seagrass, and are unsightly and smelly to humans when piled along shorelines. The eventual decay of the opportunistic biomass can cause oxygen depletion in the sediment and in the water column. Where bed sediments turn anoxic under masses of rotting macroalgae, toxic gases such as hydrogen sulphide may accumulate.

Elevated loads of fine sediment in freshwater runoff can exacerbate the symptoms of eutrophication. For instance, increased suspended-sediment concentration (which can be a consequence of increased catchment fine-sediment runoff) reduces primary production by the microphytobenthos by reducing photosynthetic efficiency (Pratt et al., 2014). As a result, there is less assimilation of ammonium and a greater efflux of ammonium from the sediment to the overlying water, which can stimulate nuisance water-column primary production (algal blooms) that impacts consumers at higher trophic levels.

Bricker et al. (1999) distinguished between primary and secondary symptoms of eutrophication. The primary symptoms are high levels of fast-growing algae, including phytoplankton (typically inferred from measurements of chlorophyll *a*), epiphytes, and/or macroalgae, which indicate the first stages of eutrophication. The secondary symptoms, which indicate a much more degraded state, include depleted dissolved oxygen, sulphide-rich sediments, and seagrass loss.

New Zealand estuaries that are vulnerable to eutrophication tend to be shallow and have clear water and/or a long residence time. Both deep estuaries and estuaries that are turbid may be able to sustain higher water-column nutrient concentrations without showing symptoms of eutrophication because they are light limited, and nutrients may be flushed from estuaries with a short residence time before algae can respond. Secondary symptoms of eutrophication may develop at the bed in deep stratified estuaries where organic matter falls out of a nutrient-enriched euphotic zone and onto the bed where it rots. In New Zealand, ICOLLs (intermittently closed and open lakes and lagoons), which are shallow and which may have a very long residence time, are the most sensitive estuary type.

Wriggle (2012) noted that many New Zealand estuaries have quite short residence times (~1 day), which means that phytoplankton are flushed from the system as fast as they can grow. Problems usually arise from the rapid growth of green and red macroalgae, which includes the genera *Enteromorpha*, *Cladophora*, *Ulva* and *Gracilaria*. Phytoplankton abundance, then, is not a reliable primary symptom of eutrophication. Wriggle recommended that, instead, epiphytes (particularly macroalgae) and bed-sediment oxygen status (as indicated by the presence of suphides and the depth to the redox potential discontinuity) be used as more reliable symptoms[1]. This requires a modification for New Zealand conditions of Bricker et al.'s method of assessing trophic state.

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[1] Although the depth to the RPD can be difficult to estimate.

Quoting Howarth and Marino (2006), Wriggle (2012) noted that nitrogen is typically the target of management strategies because nitrogen is considered to be limiting to algal growth, at least in temperate estuaries that are more-or-less permanently open to the ocean, since ocean water typically contains high concentrations of phosphorus. In ICOLLs, nitrogen and phosphorus are thought to co-limit primary production, in which case different management strategies are required. Snelder and Fraser (2013), in summarising discussions to date on estuary attributes that were being considered at the time for inclusion in the National Objectives Framework, noted that the load of total nitrogen (TN) is a "key attribute that determines ecosystem health".

Wriggle (2012) developed "nutrient load criteria" for each of three New Zealand estuary types. The three estuary types were ICOLLs, tidal lagoons and tidal rivers, which are all represented in Southland. The criteria are expressed as "areal loads" of nutrient (mass per day per surface area of the estuary) which, if not exceeded, should "limit eutrophication symptoms", where those symptoms vary somewhat by estuary type. For both the tidal lagoons and tidal rivers there is only one criterion, which is for nitrogen. For ICOLLs, there is a criterion for nitrogen and a criterion for phosphorus.

2.2 Relationship between trophic state and nutrient inputs from freshwater

Although there may be a relatively simple relationship between trophic state and freshwater nutrient inputs in a given estuary or even across estuaries that share a similar physiography, that is not likely to be the case for estuaries with different physiographies, for the reasons noted above.

Snelder et al. (2014) explored the proposition that, for at least some estuary types in the Southland region, nitrogen is the primary driver of eutrophication. Figure 2-1 shows the results, which plots "total nitrogen loading rate" against an "overall condition grade for nutrient enrichment" for seven Southland estuaries, including Waikawa, Toetoes, New River Estuary and Jacobs River Estuary.

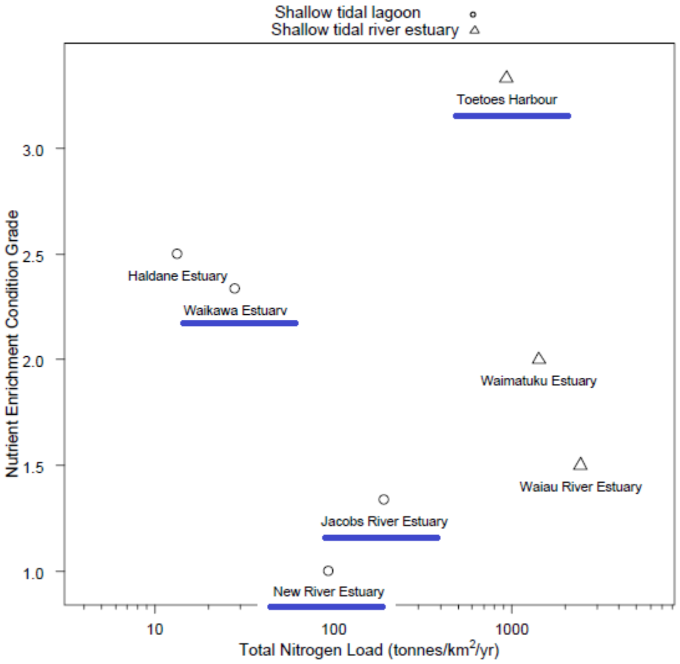


Figure 2-1: Relationship between overall condition grade for nutrient enrichment and total nitrogen loading rate. The estuaries are discriminated by type (triangle symbol denotes a shallow tidal river estuary; circle symbol denotes a shallow tidal lagoon). Figure taken from Snelder et al. (2014). The names of the four estuaries that are the subject of the ecological health assessment (New River Estuary, Jacobs River Estuary, Waikawa and Toetoes) in the companion report are underlined.

The “total nitrogen loading rate” has units of mass per year per surface area of estuary, and was developed by applying a combination of models that were validated to various degrees against SoE monitoring data (refer to Snelder et al., 2014, for details).The overall condition grade is an amalgamation of a number of individual “condition measures” (areal extent of macroalgae, sediment nutrient concentration, depth of sediment oxygen) which have been monitored in Southland estuaries for a number of years using the National Estuary Monitoring Protocol (Robertson et al., 2002). Essentially, condition measures are averaged to obtain the overall condition grade and then thresholds are applied to arrive at a descriptive rating of very good (overall condition grade > 3), good (between 2.5 and 4), fair (between 2 and 2.5), and poor (less than 2). Snelder et al. posited that estuaries with an overall condition grade of less than 2 would not meet RWP (Regional Water Plan) objectives. Both New River Estuary and Jacobs River Estuary had a poor overall condition grade for nutrient enrichment (1.0 and 1.3, respectively), indicating that they would not meet RWP objectives. Waikawa had a fair grade (2.3) and Toetoes had a very good grade (3.3).

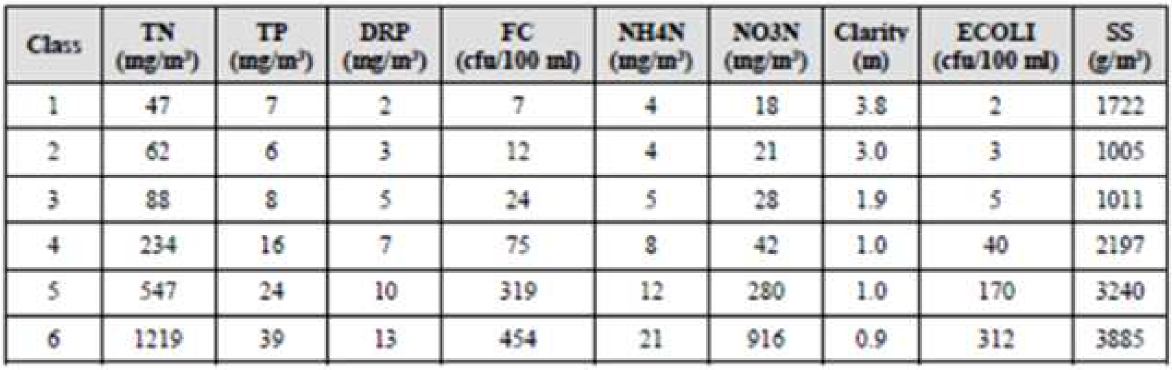
Figure 2-1 shows an approximate inverse relationship between overall condition grade and the nitrogen loading rate when estuaries of each type are considered in a group. Snelder et al. (2014) noted that Figure 2-1 also shows that shallow tidal lagoons have a higher sensitivity to nutrient inputs than shallow tidal rivers, which is consistent with the fact that shallow tidal lagoons are less well flushed than tidal rivers.

Strictly, it is not correct to draw conclusions about causal relationships from only a data plot of the likes of Figure 2-1; although understanding cause may be aided by this type of plot, it really requires knowledge of processes. Nonetheless, the mechanisms by which increases in nutrient loading lead to changes in estuary trophic state have been widely investigated and are well known, and Figure 2-1 supports the contention that land-side total nitrogen loading is at least one driver of estuary trophic state in Southland and could therefore be used as a NOF attribute for ecosystem health. The formulation of such an attribute would need proper accounting for different sensitivities of different types of estuary, and may need to be complemented with other attributes.

2.3 Trends

Snelder et al. (2014) began an analysis of trends by defining six classes of freshwater water quality in the Southland region (Table 2-1). Classes 1 and 2 represent higher water quality, predominantly water in Fiordland and water coming off mountainous areas in the region, and classes 3 to 6 represent a gradient of decreasing water quality. Figure 2-2 maps the classification. The poorest water quality is found in the streams and rivers rising on the Southland plains and inland basins (class 6), pastoral hill country (class 5) and the main stems of hill-fed rivers whose catchments have some agricultural development (class 4).

Table 2-1: Snelder et al.'s (2014) classification of freshwater water quality in the Southland region. The values are median concentrations. Table taken from Snelder et al. (2014).



Class	TN (mg/m³)	TP (mg/m³)	DRP (mg/m³)	FC (cfu/100 ml)	NH4N (mg/m³)	NO3N (mg/m³)	Clarity (m)	ECOLI (cfu/100 ml)	SS (g/m³)
1	47	7	2	7	4	18	3.8	2	1722
2	62	6	3	12	4	21	3.0	3	1005
3	88	8	5	24	5	28	1.9	5	1011
4	234	16	7	75	8	42	1.0	40	2197
5	547	24	10	319	12	280	1.0	170	3240
6	1219	39	13	454	21	916	0.9	312	3885

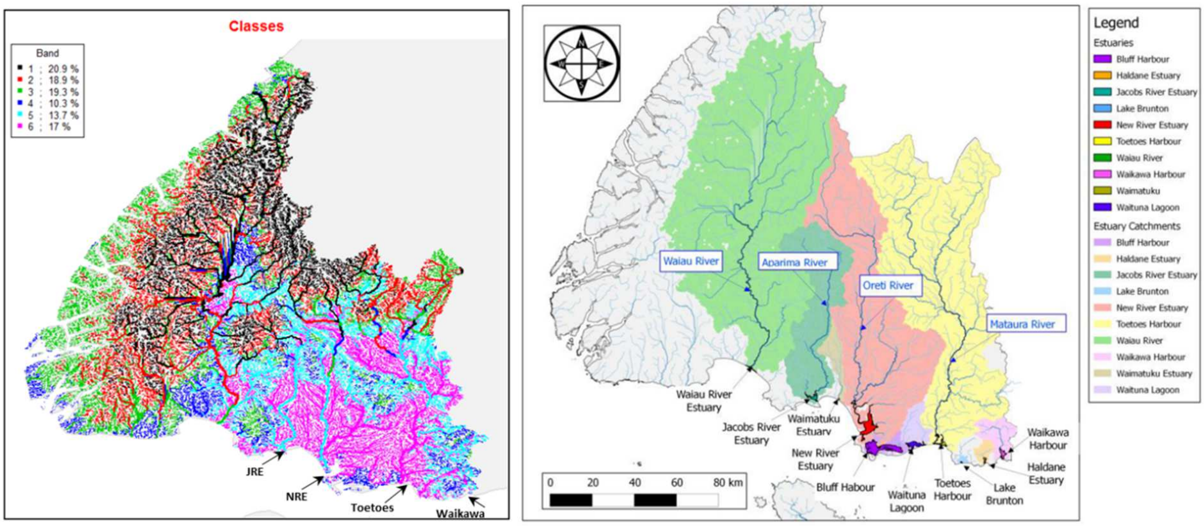


Figure 2-2: (Left panel) Snelder et al.'s (2014) classification of freshwater water quality in the Southland region. (Right panel) Location of estuaries and their respective catchments. Figures taken from Snelder et al. (2014).

Figure 2-2 also maps the location of the four estuaries that are the subject of ecological health assessment in the companion report; each drains a catchment that tends to have poor freshwater water quality[2]. Snelder et al. (2014) analysed trends in water quality by class and found that, generally, total nitrogen and nitrate were increasing in locations where water quality is already currently poor. Specifically, more than 50% of the sites in all classes except class 1 had increasing trends in total nitrogen and all classes except classes 1 and 4 had increasing trends in oxidised nitrogen. If we assume that the relationship between nitrogen loading in freshwater runoff and estuarine trophic state that is suggested by Figure 2-1 is causative, then we can expect that the trophic state of estuaries will degrade in the future if freshwater nitrogen loads do continue to increase. That may be manifest by more primary and/or secondary symptoms of eutrophication.

Palliser and Elliott (2013) used the CLUES model to predict future nutrient runoff under a range of landuse intensification and on-farm nutrient mitigation measures. TN and TP (total phosphorus)

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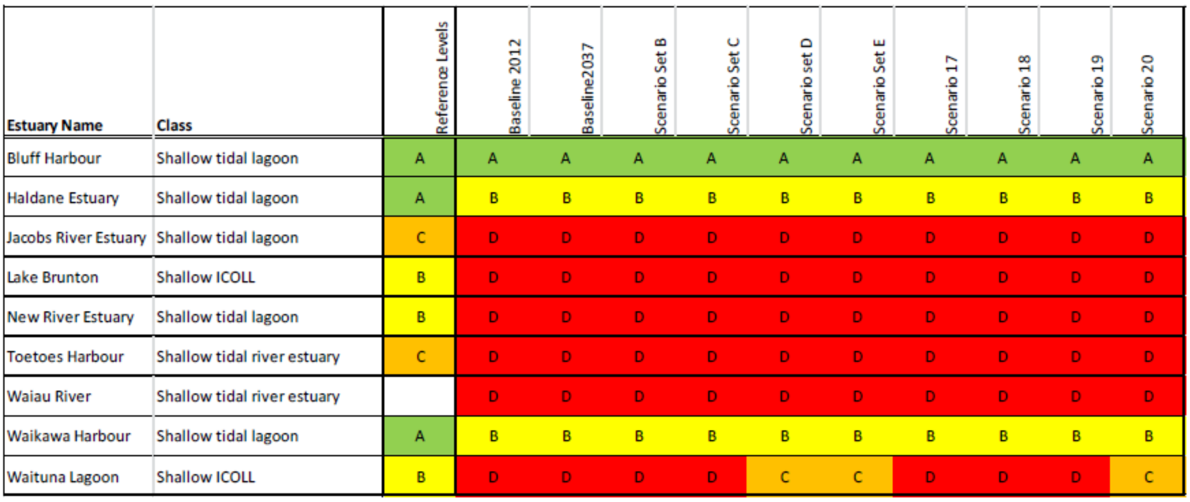
[2] The four estuaries that are the subject of ecological health assessment in the companion report are denoted by the labels "JRE", "NRE", "Toetoes" and "Waikawa" in the left panel of Figure 2-1. Each is backed by a catchment coloured predominantly blue or pink, which signify the classes with the lowest freshwater water quality in Table 2-1.

loads and concentrations in freshwater runoff were predicted to generally increase between 2012 and 2037, reflecting increased farm conversions to dairying (17% of the area in Southland in 2012 to 28% in 2037). Analysis of a number of mitigation options showed a range of responses in the terminal-reach TN loading to estuaries in the region. For some terminal reaches there was little, if any, response to mitigation because the catchments are undeveloped with no pasture and therefore no agriculture. For other terminal reaches there was an approximate halving of TN load between mitigation scenarios. This latter group includes terminal reaches that drain into Jacobs River Estuary, New River Estuary and Toetoes.

Snelder and Fraser (2013) assessed the environmental consequences of the future (i.e. 2037) nutrient runoffs predicted by Palliser and Elliott (2013). Two different systems were used in the estuary assessment: Wriggle's (2012) total-nitrogen loading criterion (which differs by estuary type, as described above), and preliminary bands for total-nitrogen loading that were being considered for inclusion in the National Objectives Framework at the time. The Wriggle (2012) criterion is a single threshold above which the estuary is considered to be unacceptably impacted by nutrients; Snelder and Fraser assumed that it can therefore be taken as being equivalent to the threshold between NOF bands C and D. Both the Wriggle criterion and the NOF bands are expressed in terms of a total-nitrogen areal loading rate. The results of the analysis are reproduced here in Table 2-2 and Table 2-3.

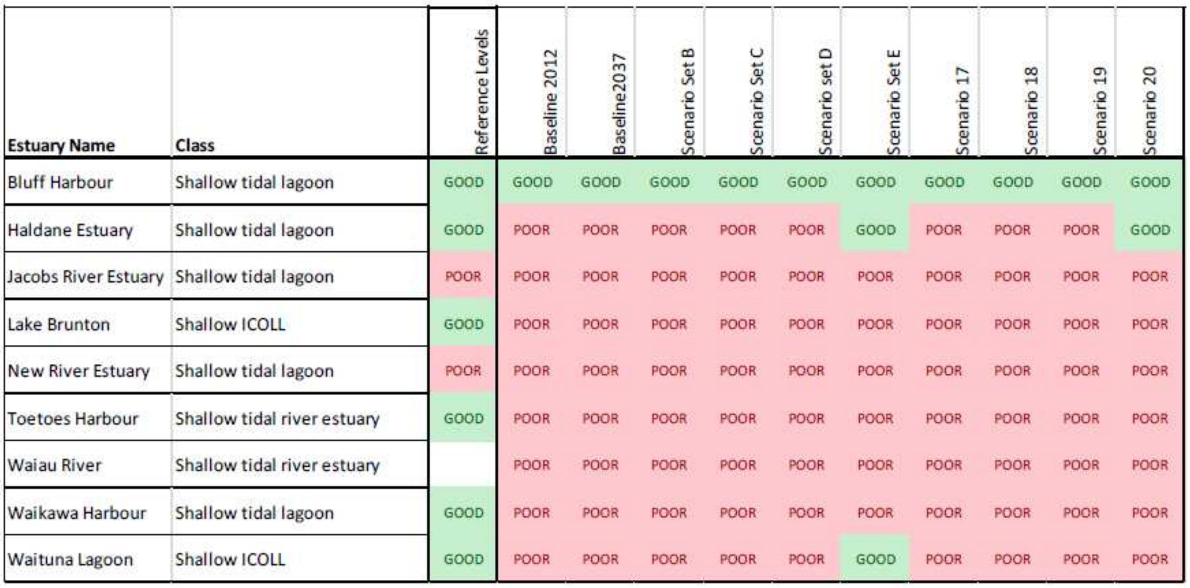
We comment in section 4.1 on how these types of predictions can and should be improved.

Table 2-2: Snelder and Fraser's (2013) predictions (for the year 2037) of estuary trophic state based on the NOF bands for total-nitrogen loading being considered at the time. The "bottom" line sits between the C and D bands, with band D below the line. Table taken from Snelder and Fraser (2013).



Estuary Name	Class	Reference Levels	Baseline 2012	Baseline2037	Scenario Set B	Scenario Set C	Scenario set D	Scenario Set E	Scenario 17	Scenario 18	Scenario 19	Scenario 20
Bluff Harbour	Shallow tidal lagoon	A	A	A	A	A	A	A	A	A	A	A
Haldane Estuary	Shallow tidal lagoon	A	B	B	B	B	B	B	B	B	B	B
Jacobs River Estuary	Shallow tidal lagoon	C	D	D	D	D	D	D	D	D	D	D
Lake Brunton	Shallow ICOLL	B	D	D	D	D	D	D	D	D	D	D
New River Estuary	Shallow tidal lagoon	B	D	D	D	D	D	D	D	D	D	D
Toetoes Harbour	Shallow tidal river estuary	C	D	D	D	D	D	D	D	D	D	D
Waiau River	Shallow tidal river estuary		D	D	D	D	D	D	D	D	D	D
Waikawa Harbour	Shallow tidal lagoon	A	B	B	B	B	B	B	B	B	B	B
Waituna Lagoon	Shallow ICOLL	B	D	D	D	D	C	C	D	D	D	C

Table 2-3: Snelder and Fraser's (2013) predictions (for the year 2037) of estuary trophic state based on Wriggle's (2012) total-nitrogen loading criterion. Table taken from Snelder and Fraser (2013).



Estuary Name	Class	Reference Levels	Baseline 2012	Baseline2037	Scenario Set B	Scenario Set C	Scenario set D	Scenario Set E	Scenario 17	Scenario 18	Scenario 19	Scenario 20
Bluff Harbour	Shallow tidal lagoon	GOOD	GOOD	GOOD	GOOD	GOOD	GOOD	GOOD	GOOD	GOOD	GOOD	GOOD
Haldane Estuary	Shallow tidal lagoon	GOOD	POOR	POOR	POOR	POOR	POOR	GOOD	POOR	POOR	POOR	GOOD
Jacobs River Estuary	Shallow tidal lagoon	POOR	POOR	POOR	POOR	POOR	POOR	POOR	POOR	POOR	POOR	POOR
Lake Brunton	Shallow ICOLL	GOOD	POOR	POOR	POOR	POOR	POOR	POOR	POOR	POOR	POOR	POOR
New River Estuary	Shallow tidal lagoon	POOR	POOR	POOR	POOR	POOR	POOR	POOR	POOR	POOR	POOR	POOR
Toetoes Harbour	Shallow tidal river estuary	GOOD	POOR	POOR	POOR	POOR	POOR	POOR	POOR	POOR	POOR	POOR
Waiau River	Shallow tidal river estuary		POOR	POOR	POOR	POOR	POOR	POOR	POOR	POOR	POOR	POOR
Waikawa Harbour	Shallow tidal lagoon	GOOD	POOR	POOR	POOR	POOR	POOR	POOR	POOR	POOR	POOR	POOR
Waituna Lagoon	Shallow ICOLL	GOOD	POOR	POOR	POOR	POOR	POOR	GOOD	POOR	POOR	POOR	POOR

Regardless of whether the Wriggle criterion is used or the NOF bands are used, and regardless of the mitigation measures adopted, only a few estuaries are predicted to be in an acceptable trophic state (i.e., achieving a NOF band of C or better, or a Wriggle "good" state).

However, Snelder and Fraser pointed out that all estuaries should achieve a NOF A band under the "reference" conditions (i.e., no human pressures), which was generally not the case (Table 2-2). This unexpected result led them to conclude that the NOF bands for the total-nitrogen attribute were likely to be too conservative. On the other hand, the reference conditions delivered more "good" states using the Wriggle criterion (Table 2-3), which suggests that this criterion actually lies closer to the division between the NOF A and B bands than the division between the C and D bands, which was what Snelder and Fraser initially assumed.

Snelder and Fraser noted that that the application of the proposed NOF bands and the Wriggle criterion is dependent on assigning estuaries to one of three estuary types and that results are likely to be very sensitive to what they called "somewhat subjective decisions" in this regard. Nonetheless, Snelder and Fraser pointed out, the existing and predicted future total nitrogen loads exceed the loads corresponding to an environmental "bottom line" (at least a NOF C band or a Wriggle fair condition) by a factor of more than two for many of the region's estuaries. Furthermore, the mitigation scenarios generally had little effect on bringing down this number, which is legitimate reason for concern for the future nutrient health of the region's estuaries.

Snelder and Legard (2014) looked further at how nutrient loads in eight large Southland catchments could be changed by on-farm mitigation measures, and the extent to which on-farm mitigation measures could offset the effects of landuse change and increasing dairy-farm production on catchment water quality. They concluded that gains in the future from on-farm mitigations could be quickly eroded by ongoing conversion of sheep and beef farms to dairy farms and production increases on dairy farms. Specifically, they found that "based on past production increases on dairy farms, it seems likely that future production increases alone could use up the additional capacity created under all the mitigation scenarios [considered in the study] in approximately a decade or less”. Snelder and Legard concluded that “under the status quo of ongoing conversions and increasing production on dairy farms, water quality will not be maintained (or improved by 10%) in the long term, even if very stringent mitigation requirements… were to be adopted”, and that limits for catchment nutrients will be required to achieve the goal of maintaining and improving water quality across the Southland region, including in the region’s estuaries.

Finally, to repeat: we comment in section 4.1 on how these types of predictions can and should be improved.

3 Sediments

3.1 Background

Estuaries receive and accumulate sediments that enter from the ocean-side and from the land-side.

Sediments that enter from the ocean-side are typically marine sands, washed in through the mouth of the estuary on a regular basis by waves and tides. Reflecting their origin, marine sands tend to accumulate in the seaward reaches of the estuary, depending on the size of the tidal prism relative to the volume of freshwater runoff, the offshore wave climate, circulation patterns around any flood-tide delta complex, and the pattern of tidal deformation throughout the estuary.

Sediments that enter from the land-side are derived from erosion of catchment rocks and soils[3], and may comprise a wide range of grainsizes[4], depending on the catchment geology, erosion processes and hydrology. Other, more minor, sources of sediment to the estuary include estuary shoreline erosion and *in situ* shell production.

Because of its very slow settling speed compared to the settling speed of sand, fine sediments tend to be dispersed and deposited by a different set of transport processes than those that disperse and deposit sand.

Tidal-current asymmetry, typically expressed in terms of an ebb- or flood-dominance (e.g., Green et al., 2000) , is understood to be the primary control on sand transport and accumulation. The development of sandbanks, channels and intertidal flats has been explained entirely in terms of the interactions between tidal currents and the seabed (e.g., Friedrichs et al., 1992; Friedrichs and Aubrey, 1994). If the estuary is relatively deep, tidal currents deform in a way that causes them to import sand into the estuary to build subtidal banks and intertidal flats. The process is self-limiting, however: as sand accumulates to build banks and flats, the water depth gets shallower overall, and the deformation of the tidal currents begins to reverse and sand tends to get transported back out to sea.

In contrast, the fate of fine sediments is governed more by slower processes and processes associated with baroclinic dynamics[5]. These include the large-scale estuarine circulation (which is driven by the distribution of salt, and therefore freshwater, throughout the estuary), river plumes, and lags that arise from the settling of fine particles and the consolidation of fine sediments on the bed. As a result, fine sediments tend to accumulate in characteristic parts of the estuary, which include the upper intertidal flats and in the estuary turbidity maximum (further discussion below).

Where there is enough fetch presented to the wind, waves will develop that are capable of resuspending both sands and fines (e.g., Green, 2011; Green and Coco, 2014). Because of its relatively large settling speed, sand may not be transported very far as a result, but with a much smaller settling speed, fines so resuspended may be transported very large distances to settle in more sheltered parts. Hence, fines do not tend to accumulate in open reaches, and waves can be seen as "cleansing" open reaches of fine sediments, with the removal of that fine sediment to other, preferred locations (Green and Hancock, 2012). Vegetation also plays an important role by baffling turbulence and wave-orbital motions, which enhances settling of fine particles and also reduces the resuspension of settled sediments (see Townend et al., 2011). Mangroves and saltmarshes act in this

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[3] Such sediments are called "terrigenous" when they settle on the seabed.

[4] Including clays, fine silts and silts, which are collectively termed "mud" or just "fine sediments".

[5] "Baroclinic" refers to a water column that is density stratified by the presence of freshwater.

way, as does nuisance macroalgae, the growth of which may be stimulated by catchment nutrient inputs.

Fine sediments eroded from the catchment and transported downstream in freshwater runoff typically enter the estuary gradually, mixing with saltwater sometimes over a considerable distance within tidal creeks and the terminal reaches of larger rivers. The mixing causes fine sediment particles in the freshwater to flocculate, or clump together, resulting in heavier, larger aggregates of particles which more readily sink to the seabed. As the aggregates sink, they fall through the mixing interface into the saltwater. Once there, they get carried landward and eventually entrained into the mixing interface and dispersed back up into the freshwater. The cycle repeats, thus trapping the river-borne fine sediment in the vicinity of the mixing interface and forming the estuarine turbidity maximum (ETM) (e.g., Wolanski et al., 1995; Uncles et al., 2006; Kitheka et al., 2005).

There are several ways fine sediment may escape the ETM, including being flushed out during periods of high freshwater runoff (e.g., Green and Hancock, 2005), settling to the bed, and being stranded on adjacent banks. Tidal rivers and creeks effectively attenuate the load of catchment fine sediment that would otherwise be dispersed within the wider estuary.

Fine sediments are responsible for virtually all of the adverse sediment-related effects on estuarine organisms and communities. Effects due to suspended fine sediments include: (1) reduction in shellfish condition, growth and ability to reproduce, clogging of fish gills, and reduction in visual clarity, which effects visual predators; (2) reduction in light penetration, which affects primary producers; and (3) reduction in photosynthetic efficiency of the microphytobenthos, which changes nutrient cycling. The effects of deposited fine sediment include: (1) progressive muddying of the seabed, which changes its biogeochemical functioning and its suitability as a habitat for a number of important species; and (2) loss of species by smothering.

At the present sea level, which has been more-or-less stationary for the past 6,000 years, significant open-coast nearshore marine sources of fine sediment are rare. Fine sediment of catchment origin that is flushed from the land to the coastal ocean is dispersed widely, and in some systems there are well-defined transport pathways ocean-wards off the continental shelf (e.g., Orpin, 2004). Fine sediment can and does enter estuaries from the ocean-side, but it will typically be of recent terrestrial origin that has previously been flushed into the coastal ocean.

Sediments progressively accumulate in estuaries, causing them to infill. Most New Zealand estuaries are currently at an advanced stage of infilling, the achievement of which has been hastened in the past century by widespread catchment deforestation that has greatly increased catchment sediment runoff (e.g., Page and Trustrum, 1997), which in turn has increased sedimentation rates relative to the typical pre-deforestation rate (e.g., Hume and Dahm, 1991; Sheffield et al., 1995).

As infilling has progressed, there have probably been changes in the balance amongst the fine-sediment deposition rate, the amount of fine sediment held in suspension in the water column and the amount of fine sediment that is flushed into the coastal ocean. A currently active area of research is aimed at understanding how the “end stages” of estuary infilling play out. One idea holds that wave scour of bed sediments, which increases as water depths reduce, could prevent the final infilling of open estuaries, but it is also clear that estuaries can be completely infilled and occupied by terrestrial vegetation.

3.2 Relationship between estuary health and fine-sediment inputs from land

In their various monitoring reports, Wriggle (and their predecessors) document and discuss a wide range of adverse effects of various severity due to fine sediments in Waikawa, Toetoes, Jacobs River Estuary and New River Estuary, and presume the source of the problematic fine sediments is the catchment. Wriggle's presumption is most likely to be correct, although there may be complicating factors. For instance, in addition to new inputs of fine catchment sediment, changes in the dynamics of the estuary could cause changes in the internal redistribution of "pre-existing" sediments that result in an increase (or decrease) in the accumulation of fine sediment at any particular site. These might include a change in circulation patterns associated with estuary infilling, changes in freshwater runoff that alter the baroclinic circulation, and loss of marginal habitat which otherwise would sequester fine sediment. In addition, there may be purely local effects, such as the growth of macroalgae that traps fine sediments. Nonetheless, we reiterate that Wriggle's presumption is most likely to be correct.

Studies have recently been conducted to identify sources of sediment that deposit in some Southland estuaries. For instance, Gibbs et al. (2014) used the CSSI technique to identify sources of sediment that deposit at four locations in Jacobs River Estuary. Gibbs et al. considered the contributions of three "external" sources (the Aparima River, the Pourakino River and the coast outside the estuary) as well as "translocation" of sediment between the four sites in the estuary. The major result was that virtually no new catchment sediment was depositing at any of the sites, with most of the sediment at each of the four sites coming either from the coast or from the other sites within the estuary. Gibbs et al. attributed this result to the short residence time of the estuary, which results in efficient flushing to the coastal ocean of the bulk of any sediments delivered in freshwater runoff.

The Jacobs River Estuary study demonstrates the importance of resolving source regions since, if the results are correct and can be generalised to the entire estuary, sediment mitigation in the catchment would have no effect on estuary sediment issues (which are many and various). However, the two sampling locations that were in the main body of the estuary (8a, on the southern flats, and 10a, in the central basin) were on hard sands between softer muds, which were not sampled. This suggests that sampling locations 8a and 10a were fundamentally unsuited for the purposes of the study, which was to identify the source of problematic fine sediment. The conclusion that there are virtually no new catchment sediments deposited at site 9a in the sheltered Pourakino arm and 6a in the sheltered northern flats does not seem to tally with the reported high sedimentation rates at both of those sites. However, the seabed at both of those sites is covered with extensive beds of macroalgae which could be enhancing the deposition of fine sediments being transported in suspension from other parts of the estuary, which would explain the results of the CSSI work.

To improve the confidence in these results, model studies of estuarine hydrodynamics and sediment transport, linked to catchment sediment runoff, need to be conducted.

3.2 Trends

Snelder et al. (2014), in an analysis that mirrored the one done for nutrients (see above), explored the relationship between the estuary "overall condition grade for sedimentation" and freshwater annual loads of suspended sediment (units of mass per year per surface area of estuary) (Figure 3-1), with a view to then assessing trends in freshwater suspended-sediment loads as an indicator of trends in estuary "sediment health".

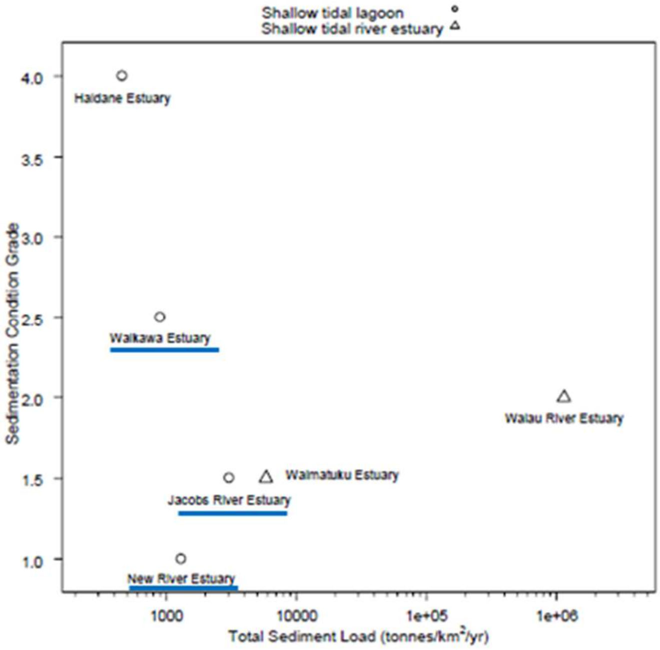


Figure 3-1: Relationship between overall condition grade for sedimentation and annual load of suspended sediment delivered by freshwater. The estuaries are discriminated by type (triangle symbol denotes a shallow tidal river estuary; circle symbol denotes a shallow tidal lagoon). Figure taken from Snelder et al. (2014). The names of the four estuaries that are the subject of the ecological health assessment (New River Estuary, Jacobs River Estuary, Waikawa and Toetoes) in the companion report are underlined.

As was the case for the overall condition grade for nutrient enrichment, the overall condition grade for sedimentation is an amalgamation of a number of individual "condition measures" (including area of soft mud and sedimentation rate). The suspended-sediment loads were derived from a nonparametric regression model built from SoE monitoring data.

Figure 3-1 does not show any clear relationship between the annual suspended-sediment load and the sedimentation condition grade in either of the two estuary types represented in the figure. Snelder et al. surmised that the reason might be that the fate of sediments in estuaries is complex (particularly the degree to which sediments are trapped or flushed) and not well represented by the simple estuary types. They also noted that the regression model for the suspended-sediment loads "performed poorly". Given the result from Figure 3-1 and the lack of confidence in the suspended-sediment loads, it does not seem defendable to infer trends in estuary "sediment health" from trends in freshwater suspended-sediment loads, which Snelder et al. had intended. Even if there were a stronger relationship, a deeper understanding of processes would still be required to demonstrate causation rather than just correlation, and from there to predict trends.

A first step towards improving the understanding the drivers of estuary sediment health could be turning to process-based model predictions of sediment runoff. Although CLUES model predictions of catchment sediment runoff are mentioned in some of the Wriggle (and predecessor) monitoring reports, to our knowledge there has been no systematic process-based model studies of catchment sediment loads and past trends in loads to the four study estuaries, which could help with understanding the estuarine monitoring data. Neither have there been predictions of future trends, which could assist management in designing intervention. The opposite is the case for nutrients, where freshwater nutrient loads have been linked to estuary eutrophic state, and significant work has been done forecasting future nutrient loads and how these are likely to be increased by future landuse intensification and change and decreased by mitigation.

A number of studies in other regions have demonstrated the value of process-based model studies. For instance, in the Tauranga Sediment Study, NIWA used the GLEAMS sediment model to predict catchment sediment runoff to Tauranga Harbour under a number of scenarios that included ongoing urbanisation of parts of the catchment and climate change. The sediment was dispersed in the harbour using a hydrodynamic model that had been modified to work at the "planning timescale" (decades), which resulted in the identification of estuary habitats that are particularly vulnerable to sediments and that are connected, by transport pathways, to different sediment source regions in the catchment. Management used the results to target intervention appropriately in the catchment. NIWA used two catchment models (GLEAMS and the Contaminant Load Model) in a series of studies for Auckland Regional Council aimed at predicting sedimentation and heavy-metal accumulation in the region's harbours under different urbanisation and stormwater mitigation scenarios. The studies revealed the parts of the harbours that were most at risk of sediment impacts and identified which parts of the catchment should be targeted for mitigation to reduce the risk. Landcare Research is currently using the SedNetNZ catchment sediment model in the Northland Sediment Study to predict sediment runoff to Whangarei Harbour. The model is being linked to a harbour model being developed by NIWA and the results will be incorporated into a wider catchment economic model to predict the costs of achieving a range of sediment-related targets in Whangarei Harbour and the rivers and streams that drain into the harbour.

The SedNetNZ catchment sediment model is probably the best of the process-based catchment-scale models available at present. It has a good physical basis, accounting for sediment retention in reservoirs and lakes and on channel beds and floodplains. It also accounts for what is arguably the majority of erosion processes in the New Zealand landscape, which are sheet and rill erosion, landslides, earthflows, gullies and bank erosion. Bank erosion is an important component, which has not been explicitly treated by previous models, including GLEAMS. A potential significant difficulty is accounting for lags in the movement of sediment down the catchment, which Gibbs et al. (2014) noted the importance of in the catchment of the Aparima River. Gibbs et al. found evidence of a change in the isotopic signature of riverbed sediments from sheep landuse to dairying in the upper reaches of the catchment, but lower down in the catchment the signature was still dominated by sheep despite significant dairy conversion in the catchment. They attributed this to a time lag in the transport downstream of sediment sourced from dairy farms, which they predict will, over time, overwrite the sheep signature.

4 Recommendations

4.1 Nutrients

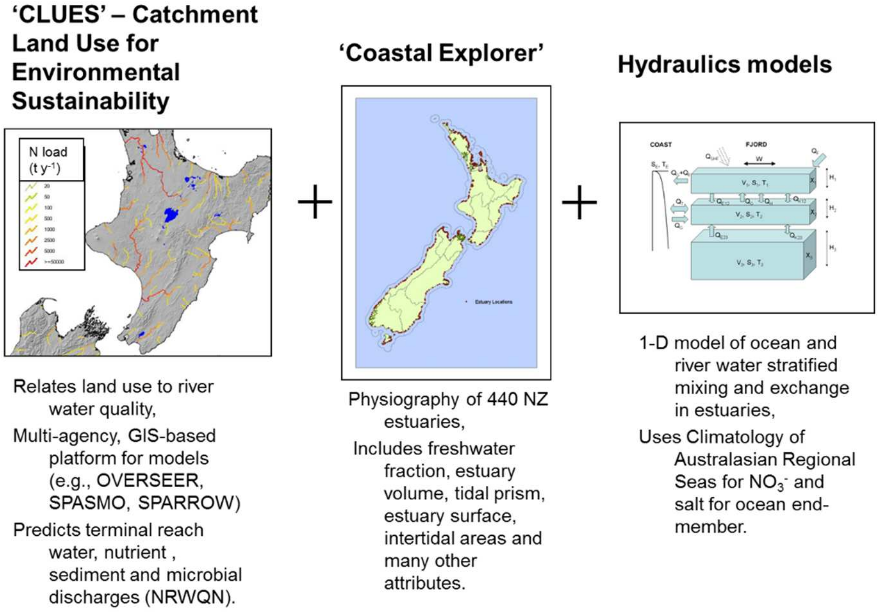
Refinement of the predictions of future trophic state and development of the ecological condition gradient for use in limit setting will require (1) a better assessment of the way terminal-reach nitrogen loading rates convert into estuary water-column concentrations and the way water-column concentrations fuel algae growth and the associated development of secondary symptoms of eutrophication, and (2) assessing the store of nutrients in the estuary bed sediments and the importance of bed-sediment nutrient dynamics.

For example, the predictions of future trophic state based on total-nitrogen loading given in Table 2-2 and Table 2-3 should be revisited by accounting for, at least, the characteristic residence time of land-origin nitrogen in the estuary system, the seasonality of nutrient supply and algal growth potential and how these overlap, and the contribution of internal nutrient sources to primary production. This would result in process-based predictions that are more robust than predictions based on simple total-nitrogen loading criteria of the type implicit in Figure 2-1 or articulated in the NOF or by Wriggle.

Furthermore, process-based understanding of the physical characteristics and nutrient dynamics of Southland estuaries could provide a more robust and nuanced method for setting limits than an ecological condition gradient approach that is based only on correlation relationships (as opposed to causative relationships). A key issue regarding limit-setting is the extent to which, if any, Southland estuaries might simply “reverse” condition following any reduction in land-side nutrient loading, as opposed to following a path that constitutes a hysteresis loop.

Vis-à-vis these comments, we note:

> (1) Tools that will improve predictions and assist with limit setting are available or in development:
>
> - The CLUES–Estuaries tool (Figure 4-1 and http://www.niwa.co.nz/our-science/coasts/research-projects/estuarine-water-quality-the-clues-estuary-tool) is designed to predict estuarine “potential” nutrient concentrations under different catchment landuses. The CLUES model provides predictions of freshwater runoff and associated nutrient loadings which, together with seasonally-adjusted oceanic values of nitrate and salt taken from the CSIRO Australian Regional Seas Climatology (http://www.marine.csiro.au/~dunn/cars2009/), are mixed in the estuary. Mixing is based on a steady-state dilution factor to estimate concentrations of total nitrogen given input loads and certain physiographic attributes of the estuary. A new version of the model about to be implemented will calculate the dilution factor as a function of flow. The CLUES catchment load model is currently designed for mean annual loads but is in the process of being seasonalised. The principles behind the mixing models are, however, valid over shorter timescales, particularly in estuaries with a high degree of flushing, which is the case for many of the Southland estuaries.



Relates land use to river water quality,
Multi-agency, GIS-based platform for models (e.g., OVERSEER, SPASMO, SPARROW)
Predicts terminal reach water, nutrient , sediment and microbial discharges (NRWQN).

Physiography of 440 NZ estuaries,
Includes freshwater fraction, estuary volume, tidal prism, estuary surface, intertidal areas and many other attributes.

1-D model of ocean and river water stratified mixing and exchange in estuaries,
Uses Climatology of Australasian Regional Seas for NO_3^- and salt for ocean end-member.

Figure 4-1: Overview of CLUES–Estuaries.

- NIWA is currently coupling an estuarine nutrient transport (Delft Delwaq) with a macroalgal growth model (Ren et al., 2014) for predicting conservative and non-conservative nutrient transport and macroalgal growth and biomass in estuaries. The model will predict spatial patterns and temporal changes of macroalgal growth and biomass, which is a primary symptom of eutrophication.
- The Envirolink-funded Estuarine Trophic Index project (2-year project, initiated in late 2014) aims to assist in:
  1. Determining the current nutrient status of estuaries.
  2. Making assessments of the nutrient effects in estuaries associated with landuse intensification and change.
  3. Considering the consequences to estuaries of freshwater nutrient limits.
  4. Setting nutrient load limits for estuaries.

  For this, a two-piece Estuary Trophic State Toolbox is being developed. (Figure 4-2). The first tool in the Toolbox will consist of two reports, one report providing guidance on how to type an estuary, and one report providing a rating system for physical susceptibility to eutrophication with an accompanying explanatory narrative, and an indicator list with guidelines for monitoring. The second tool in the Toolbox will be a software package for evaluating an Estuarine Trophic Index (ETI) score from values of indicators. The software will include a Bayesian Network (BN) that predicts indicator values from a range of input data. The BN may be used when actual indicator data are not available.

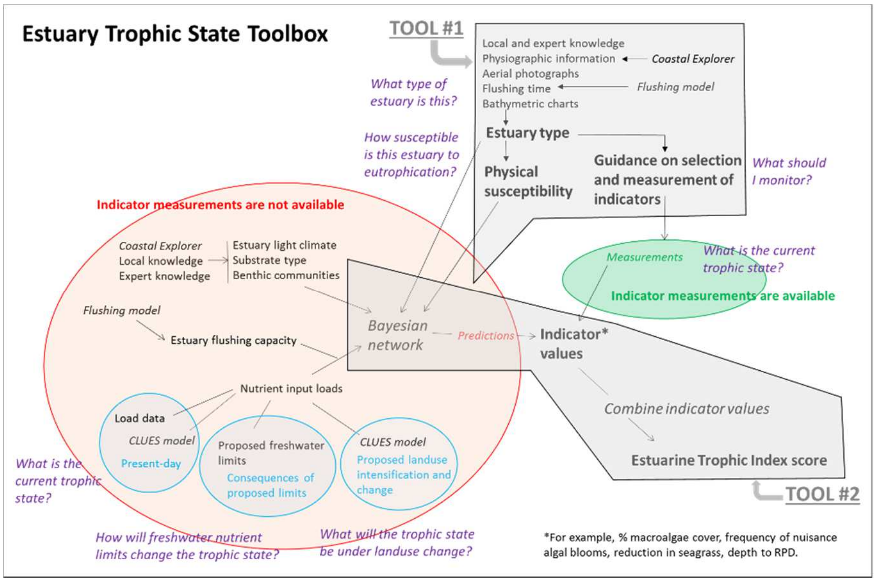


Figure 4-2: The Estuary Trophic State Toolbox.

(2) The seabed can act as both a source and sink of nutrients to the estuary system that is additional to the external land-side and ocean-side nutrient sources.

It is particularly important to understand the seabed nutrient dynamics when trying to predict how the estuary might respond to management of land-side nutrient sources. For instance, eutrophication is ameliorated by denitrification, which results in the release of gaseous N_2 to the water column and ultimately the atmosphere, hence removing nitrogen from the system. Denitrification is driven by microbial processes at the oxic/suboxic boundary in the seabed sediments. Denitrification "efficiency[6]" decreases with increased carbon loading (Eyre and Ferguson, 2002) and the attendant anoxia in bottom waters. This results in the system becoming less able to vent gaseous nitrogen to the atmosphere, and a corresponding reduction in the system's resistance to eutrophication (Seitzinger, 1988). The atmosphere is the ultimate sink for the nitrogen liberated by denitrification, but processes operating in the seabed send nitrogen to that sink.

On the other hand, and as noted previously, elevated suspended-sediment concentrations can reduce primary production by the microphytobenthos by reducing photosynthetic efficiency (Pratt et al., 2014). As a result, there is less assimilation of ammonium and a greater efflux of ammonium from the sediment to the overlying water column.

Improving our understanding of seabed nutrient dynamics in Southland estuaries will improve our ability to predict how estuaries will respond to management of land-side nutrient inputs.

(4) Virtually nothing is known about restoration trajectories that might be followed by New Zealand estuaries following a reduction in land-side nutrient inputs. At the time of writing, a 6-year research programme has been proposed to MBIE by a consortium of researchers for consideration for funding that is designed to address that knowledge gap.

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[6] Denitrification efficiency is the percentage of the total nitrogen flux that is denitrified.

4.2 Sediments

- A process-based catchment sediment model is required to provide information on sediment loads and past trends in loads to the four study estuaries. Combined with an estuary sediment transport model that explains dispersal, accumulation and flushing of fine sediment, the loads will improve the understanding of drivers of estuary sediment health, which is currently rudimentary, and will assist with development of the ecological condition gradient.

- Predictions by a catchment sediment model of future trends in sediment loads will assist management in designing intervention.

- Following the type of procedure devised by Green (2013), a catchment sediment model could be combined with a process-based understanding of estuary sediment transport patterns in a “source-to-sink” model that could be used to determine catchment sediment load limits that would achieve estuary sedimentation targets. The same type of model could be used to test and explore scenarios in a community collaborative process.

5 References

Bricker, S.B., Clement, C.G., Pirhalla, D.E., Orlando, S.P., Farrow, D.R.G. (1999) National Estuarine Eutrophication Assessment. Effects of Nutrient Enrichment in the Nation's Estuaries. NOAA, National Ocean Service, Special Projects Office and National Centres for Coastal Ocean Science, Silver Spring.

Eyre, B.D., Ferguson, A.J.P. (2002) Comparison of carbon production and decomposition, benthic nutrient fluxes and denitrification in seagrass, phytoplankton, benthic microalgae- and macroalgae-dominated warm-temperate Australian lagoons. *Marine Ecology Progress Series*, 229: 43–59.

Friedrichs, C.T., Lynch, D.R. and Aubrey, D.G. (1992) Velocity asymmetries in frictionally-dominated tidal embayments: longitudinal and lateral variability. **In**: D. Prandle (Ed.), Dynamics and exchanges in estuaries and the coastal zone, Coastal and Estuarine Studies. Springer-Verlag, New York, pp. 277–312.

Friedrichs, C. T., Aubrey, D. G. (1994) Tidal propagation in strongly convergent channels. *Journal of Geophysical Research: Oceans* (1978–2012), 99 (C2), 3321–3336.

Gibbs. M., Olsen, G., Stewart, M. (2014) Jacobs River Estuary Sediment Sources Assessment. *NIWA Client Report* HAM2014-003, prepared for Dairy NZ, NIWA Hamilton.

Green, M.O. (2011) Dynamics of very small waves and associated sediment resuspension on an estuarine intertidal flat. *Estuarine, Coastal and Shelf Science*, 93(4): 449–459.

Green, M.O. (2013) Catchment sediment load limits to achieve estuary sedimentation targets. *New Journal of Marine and Freshwater Research*, 47(2): 153–180.

Green, M.O. and Hancock, N.J. (2012) Sediment transport through a tidal creek. *Estuarine, Coastal and Shelf Science*, 109: 116–132.

Green, M.O. and Coco, G. (2014) Review of wave-driven sediment resuspension and transport in estuaries. *Reviews in Geophysics*, 52, 77–117, doi: 10.1002/2013RG000437.

Green, M.O.; Bell, R.G.; Dolphin, T.J.; Swales, A. (2000) Silt and sand transport in a deep tidal channel of a large estuary (Manukau Harbour, New Zealand). *Marine Geology*, 163: 217–240.

Howarth, R.W., Marino, R. (2006) Nitrogen as the limiting nutrient for eutrophication in coastal marine ecosystems: Evolving views over three decades. *Limnology and Oceanography*, 51: 364–376.

Hume, T.M., Dahm, J. (1991) An Investigation into the Effects of Polynesian and European Land Use on Sedimentation in Coromandel Estuaries. Consultancy Report No. 7106, *Department of Conservation*, Wellington.

Kitheka, J. U., Obiero, M. and Nthenge, P. (2005) River discharge, sediment transport and exchange in the Tana Estuary, Kenya. *Estuarine, Coastal and Shelf Science*, 63, 455–468.

Orpin, A. R. (2004) Holocene sediment deposition on the Poverty-slope margin by the muddy Waipaoa River, East Coast New Zealand. *Marine Geology* 209.1 (2004): 69–90.

Page, M.J., Trustrum, N.A. (1997) A late Holocene lake sediment record of the erosion response to land use change in a steep catchment, New Zealand. *Zeitschrift für Geomorphologie* 41: 369–392.

Palliser, C., Elliott, S. (2013) Water Quality Modelling for the Southland Region. *NIWA Client Report* No. HAM2013-021, prepared for Ministry for the Environment, June 2013, NIWA Hamilton.

Pratt, D.R., Lohrer, A.M., Pilditch, C.A., Thrush, S.F. (2014) Changes in ecosystem function across sedimentary gradients in estuaries. *Ecosystems*, 17: 182–194.

Ren, J.S., Barr, N.G., Scheuer, K., Schiel, D.R., Zeldis, J. (2014) A dynamic growth model of macroalgae: Application in an estuary recovering from treated wastewater and earthquake-driven eutrophication. *Estuarine, Coastal and Shelf Science*, 148: 59–69.

Robertson, B.M., Gillespie, P.A., Asher, R.A., Frisk, S., Keeley, N.B., Hopkins, G.A., Thompson, S.J., Tuckey, B.J. (2002) Estuarine Environmental Assessment and Monitoring: A National Protocol. Prepared for supporting Councils and the Ministry for the Environment. Sustainable Management Fund Contract No 5096.

Seitzinger, S. (1988) Denitrification in freshwater and coastal marine ecosystems: Ecological and geochemical significance. *Limnology and Oceanography*, 33: 702–724.

Sheffield, A.T., Healy, T.R., McGlone, M.S. (1995). Infilling rates of a steepland catchment estuary, Whangamata, *New Zealand. Journal of Coastal Research*, 11(4): 1294–1308.

Snelder, T., Fraser, C. (2013) Environment Assessment of Farm Mitigation Scenarios in Southland. Aqualinc Report No. C13042/2, prepared for Ministry for the Environment, June 2013, Christchurch.

Snelder, T., Fraser, C., Hodson, R., Ward, N., Rissman, C., Hicks, A. (2014) Regional Scale Stratification of Southland’s Water Quality – Guidance for Water and Land Management. *Aqualinc Report* No. C13055/02, prepared for Southland Regional Council, March 2014, Christchurch.

Snelder, T., Legard, G. (2014) Assessment of Farm Mitigation Options and Land Use Change on Catchment Nutrient Contaminant Loads in the Southland Region. *Aqualinc Report* No. C13055/04, prepared for Southland Regional Council, March 2014, Christchurch.

Townend, I., Fletcher, C., Knappen, M., Rossington, K. (2011) A review of salt marsh dynamics. *Water and Environment Journal*, 25, 477–488.

Uncles, R. J., Stephens, J. A., Law, D.J. (2006) Turbidity maximum in the macrotidal, highly turbid Humber Estuary, UK: flocs, fluid mud, stationary suspensions and tidal bores. *Estuarine, Coastal and Shelf Science*, 67, 30–52.

Wolanski, E., King, B., Galloway, D. (1995) Dynamics of the turbidity maximum in the Fly River Estuary, Papua New Guinea*. Estuarine, Coastal and Shelf Science*, 40, 321–337.

Wriggle Coastal Management. (2012) Preliminary Guidance Document: Nutrient Load Criteria to Limit Eutrophication in Typical NZ Estuary Types – Tidal Lagoon and Tidal River Estuaries. Prepared by Wriggle Coastal Management for Environment Southland.