Kakanui Estuary Review

Prepared for Otago Regional Council

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Executive summary

The Kakanui Estuary experiences poor water quality, including blooms of suspended and benthic algae. Otago Regional Council is seeking to work with the community to outline potential next steps for managing the health of this estuary. To assist with this, Otago Regional Council requested NIWA review and summarise findings from three previous reports on the Kakanui Estuary, along with other work related to water quality of the estuary.

No single intervention is likely to prevent algal blooms in the Kakanui Estuary. Mechanical opening may reduce the frequency and intensity of phytoplankton blooms by allowing the estuary to flush more rapidly and decrease nutrient concentrations in the estuary via greater dilution by seawater. However, this is unlikely to be sufficient to prevent macroalgal blooms from occurring.

Minimum flows are set for the Kakanui River, below which permitted takes cease. Flow supplementation by increasing these minimum flows, or possibly by adding water from a low nutrient water source, could assist in reducing estuary nutrient concentrations; however, the flow increases required may be large.

Reductions in nutrient concentrations in the Kakanui River (and Waiareka Creek) by up to 2/3rds from 2017-2021 median values are likely to be required to restrict the growth of macroalgae, assuming the estuary is well mixed. However, incomplete mixing within the estuary is likely to result in reductions in algal growth in some parts of the estuary under smaller load reductions. A more-accurate understanding of the load reductions required to reduce macroalgal growth in different areas of the estuary could be achieved by coupling the estuary hydrodynamic model with a macroalgal growth model.

We note that nutrient concentrations during the 2014-2016 summer were lower than the 2017-2021 median, and close to those required to restrict macroalgal growth. We suggest closely investigating nutrient and flow data from this period, in conjunction with information of changes in land-use practices during and since that time, to determine why nutrient concentrations were low during that period and how this might be replicated in the future.

1 Introduction

The Kakanui Estuary experiences poor water quality, including blooms of suspended and benthic algae. Otago Regional Council is seeking to work with the community to outline potential next steps for managing the health of this estuary. To assist with this, Otago Regional Council requested NIWA review and summarise findings from three previous reports on the Kakanui Estuary, place these in context of other reports and data available for the estuary and provide a summary of overall recommendations based on these reports.

In this report, we summarise the findings from three previous reports where NIWA used a hydrodynamic model of the Kakanui Estuary to investigate the drivers of water quality issues in the estuary (Plew and Barr 2015; Plew 2016; Plew and Duncan 2017).

We also refer to other reports and data relating to the water quality in the estuary (Steward 2009; Ozanne 2012a; Ozanne and Wilson 2013; Roberts, Stevens et al. 2021) and the catchment (Ozanne 2012a; Ozanne and Wilson 2013; Mager 2021) to place the findings of NIWA's work in the context of other monitoring. We will also refer, when relevant, to Otago Regional Council's State of the Environment water quality data for the Kakanui River and Waireka Creek.

In the following sections of this report, we describe the work done in each of the three NIWA reports, discuss how these reports relate to each other, consider the findings of those reports in the context of recent estuary and tributary monitoring, and summarise the overall recommendations based on the reports reviewed.

2 Drivers of eutrophication

Eutrophication is an over-enrichment of nutrients causing excessive growth of aquatic algae and plants. In the Kakanui Estuary, this results in large mats of macroalgae that grows on the estuary intertidal and subtidal bed, and phytoplankton blooms (micro-algae suspended in the water column) which cause the water to become green or brown and less clear. This excessive growth of algae can lead to other ecologically detrimental impacts such as water column and sediment deoxygenation, which is harmful to estuary fauna and flora.

Algae require suitable conditions to grow, including sufficient light, appropriate water temperature and salinity, water velocities, substrate, and nutrients (particularly nitrogen and phosphorus). Of these, nutrients are the factor most amenable to management and control. Macroalgae have high nitrogen (N) requirements compared to phosphorus (P) (Atkinson and Smith 1983), and macroalgal growth is more commonly limited by N rather than P in New Zealand estuaries (Barr 2007; Robertson and Savage 2018). Similarly, N limitation is far more common than P-limitation for estuarine phytoplankton (NRC 2000; Plew, Zeldis et al. 2020). Coastal waters around New Zealand generally contain sufficient P to support algae growth, but N availability is low. In estuaries where seawater and riverine water mix, the oceanic P in combination with catchment-sourced N creates favourable conditions for algae growth. Consequently, where management of nutrient inputs to address estuary eutrophication is considered, control of catchment N inputs is likely to be more effective than controlling catchment P inputs.

To assist in determining appropriate N limits to reduce the risk of eutrophication in estuaries, NIWA has suggested in-estuary N concentration bands corresponding to different levels of algal growth rates, if no other factor (such as light, substrate, temperature, or other nutrients) limits growth.

During the 2015 study of the Kakanui Estuary (Plew and Barr 2015), draft estuary dissolved inorganic nitrogen (DIN) concentration bands were proposed for managing macroalgal growth (Table 2-1). These concentration bands were informed by previous work including Morand and Briand (1996); and Barr, Dudley et al. (2013). The 2015 study recommended reducing in-estuary DIN concentrations to <70 mg/L to restrict growth rates of *Ulva* spp. to a low to moderate rate. Growth rates of macroalgae are largely driven by nitrogen pools stored in the algal tissue. The tissue concentrations can be related to water column concentrations as greater availability of water column nutrients allows greater uptake rates into tissue and hence tissue content (Dudley, Barr et al. 2022).

Table 2-1: Bands for tissue nitrogen concentration and in-estuary Dissolved Inorganic Nitrogen (DIN). Bandings are derived for *Ulva* spp. and relate water column DIN concentrations with tissue-N content, and from Plew and Barr (2015).

Potential growth rate	Low	Low to moderate	Moderate to high	High
Ulva tissue-N (%)	< 1	1 – 2	2 – 3	> 3
DIN (µmol/L)	< 2	2 – 5	5 – 15	> 15
DIN (mg/m^3)	< 28	28 – 70	70 – 210	> 210

{Plew, 2015 #2020} made predictions of in-estuary water column nutrient concentrations using a hydrodynamic model to determine the relative portions of oceanic and riverine water. In this analysis, DIN was treated as conservative within the estuary (movement of dissolved nitrogen from water to the atmosphere via denitrification or to plant tissue via uptake were ignored). As such, concentrations calculated using the model can be considered "potential" concentrations. Because uptake and denitrification often cause substantial reductions in dissolved nitrogen concentrations in estuaries, Plew and Duncan (2017) suggested that the DIN target could be increased to 90 mg/m^3 if considering potential (i.e., derived from river and ocean concentrations) rather than measured concentrations in the estuary.

A recent study on *Agarophyton* spp., two closely related red algae found in some Otago and Southland estuaries, suggests similar nutrient bands to those in Table 2-1 (Dudley, Barr et al. 2022). Growth of *Agarophyton* spp. ceased at external DIN concentrations of ~ 20 mg/m^3, and 67% of maximum growth rate was obtained at 60 mg/m^3.

These concentration thresholds, derived from experiments investigating the effects of nutrient concentrations on growth rates of macroalgae, provide guidance on the likely response of algae to local nutrient concentrations. Concentrations vary over time and location within estuaries, and algal growth rates will also vary.

More recently, guideline concentration thresholds for nuisance macroalgae were developed as part of the Estuary Trophic Index (ETI). These thresholds were developed for estuary-averaged potential TN and potential nitrate concentrations derived from annual loads and mean flow conditions, and comparing these with macroalgae Ecological Quality Rating (EQR) which is a combined metric incorporating macroalgal cover and biomass (Plew, Zeldis et al. 2020).

Table 2-2: ETI band thresholds for nuisance macroalgae based on potential nitrogen concentrations. From Plew, Zeldis et al. (2020).

Susceptibility band	A	B	C	D
Ecological quality rating (EQR)	1.0 – 0.8	0.8 – 0.6	0.6 – 0.4	< 0.4
Potential TN (mg/m^3)	≤ 80	80 – 200	200 – 320	> 320
Potential NO_3 (mg/m^3)	≤ 65	65 – 165	165 – 260	> 260

More recent work, incorporating observations from a wider range of estuaries, suggests that the initial band thresholds are overly conservative, and higher thresholds have been suggested (Roberts, Stevens et al. 2022). Work is currently underway to refine these thresholds, but indicative values are given in Table 2-3.

Table 2-3: Draft revised ETI band thresholds for nuisance macroalgae. Based on a wider range of data from Roberts, Stevens et al. (2022) and further unpublished analysis by Leigh Stevens (Salt Ecology) and David Plew (NIWA).

Susceptibility band	A	B	C	D
Ecological quality rating (EQR)	1.0 – 0.8	0.8 – 0.6	0.6 – 0.4	< 0.4
Potential TN (mg/m^3)	≤ 250	250 – 450	450 – 650	> 650
Potential NO_3 (mg/m^3)	≤ 200	200 – 370	370 – 530	> 530

It is important note that the potential nitrogen concentrations bands in Table 2-2 and Table 2-3 are derived using mean flow and annual loads, represent an estuary volume-averaged concentration, are higher than the concentrations observed in summer when flows are lower, and do not account for uptake of nutrients. They are also intended to be used to predict the risk of eutrophication at a regional or national scale and are not directly comparable with the values proposed by Plew and Barr (2015) (Table 2-1).

Phytoplankton concentrations in estuaries are more difficult to predict. As well as light, salinity, temperature and nutrient availability, abundance of phytoplankton in estuaries is related to estuary flushing time. Phytoplankton blooms are not likely to occur in estuaries with a flushing time less than the phytoplankton doubling or turn-over time (Cloern 1996; Ferreira, Wolff et al. 2005). The ETI uses a simple growth model that incorporates nitrogen and phosphorus concentrations and estuary flushing time to predict the likely maximum potential phytoplankton biomass as an indicator of the risk of phytoplankton blooms (Plew, Zeldis et al. 2020). The model shows that phytoplankton growth does not occur if the flushing time of the estuary is short (less than ~ 3.3 days) as phytoplankton is flushed from the estuary faster than it can grow (Figure 2-1). At long flushing times, the phytoplankton concentration becomes independent of flushing time.

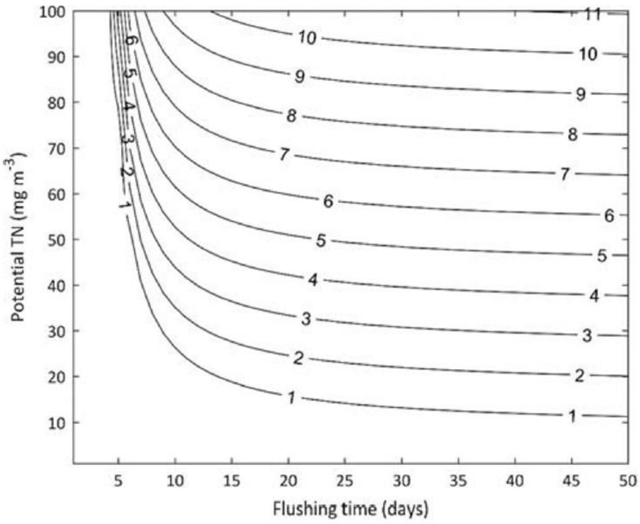

Figure 2-1: Contours of predicted chlorophyll-a concentrations (µg/L) as a function of potential total nitrogen concentration and estuary flushing time. The figure shows chlorophyll concentrations when phosphorus is not limiting. Phytoplankton does not accumulate in the estuary if the flushing time is shorter than the phytoplankton doubling time of ~ 3.3 days. From Plew, Zeldis et al. (2020).

3 Previous NIWA reports

3.1 Kakanui Estuary hydrodynamic model

3.1.1 Background

Otago Regional Council engaged NIWA to conduct a study of the Kakanui Estuary in 2015 in response to high algae growth observed in summer months. Large mats of *Ulva intestinalis* had been observed over much of the estuary bed, and at times suspended algae concentrations were also high. The purpose of this study was to provide information relating estuarine water quality with river flows and nutrient loads.

NIWA conducted a bathymetric survey of the Kakanui Estuary on 3-4 February 2015. The data from this survey were used to create a three-dimensional hydrodynamic model of the estuary. The model was calibrated using water level loggers installed at three sites in the estuary from 16 October 2014 to 3 Feb 2015, and salinity/temperature loggers installed at the Kakanui River Bridge over the same period (although near-surface and near-bed loggers were installed, the near-bed logger failed and data are only available for the near-surface sensor at 0 to 0.8 m depth, depending on water level). Salinity profiles were also collected throughout the estuary on 3-4 Feb 2015. The hydrodynamic model was run for a range of Kakanui River flows with four different mouth configurations (closed and three open mouths of different size) to determine the likely concentrations and distributions of nutrients within the estuary. NIWA also conducted tissue nitrogen, carbon and isotype analyses of *Ulva* collected from 20 locations in the estuary to determine the relative availability of nitrogen to support algal growth, and whether it was possible to determine if nitrogen was sourced from the river as opposed to the ocean.

3.1.2 Key findings

Ulva samples collected from the Kakanui Estuary on 4 Feb 2015 indicated moderate (to high in some cases) levels of nitrogen availability. Concentrations of nitrogen in the algal tissue would support moderate to high algal growth rate. Tissue nitrogen and carbon concentrations were higher in the estuary than at a nearby coastal reference site. It did not appear that riverine nitrogen was isotopically different from marine water (based on comparing *Ulva* samples collected in the estuary to a sample collected from the coast). Collectively, the tissue nitrogen, carbon and isotope analysis support the hypothesis that growth of *Ulva* in the estuary was due to nitrogen loads from the catchment rather than ocean.

The water level data showed how the estuary changes between a tidally dominated state when the mouth is open to the sea, to micro-tidal or non-tidal as the month constricts or closes. Water samples collected by Otago Regional Council at the Kakanui Bridge showed high nutrient concentrations, particularly for total nitrogen (TN) and total dissolved nitrogen (TDN) during periods when the tidal range was small or absent. This suggests that nutrients are largely sourced from the river rather than the ocean, as exchange with the ocean and hence input of seawater decreases as the tidal range becomes smaller.

The model gives insight into how nutrient concentrations will vary throughout the estuary. By weighting the nutrient concentrations in Kakanui River, Waiareka Creek and ocean by the volume fraction at each location in the estuary (e.g., Figure 3-1), maps of potential nutrient concentrations can be calculated. With nutrient concentrations in the Kakanui River and Waiareka Creek being much higher than in the ocean, nutrient concentrations are highest in the upper part of the estuary (above the bridge) and lower near the mouth. Low salinity (< 5, or a seawater fraction below ~0.15) also inhibits macroalgal growth, thus the macroalgae growth is likely to be highest in a region in the lower-mid portion of the estuary.

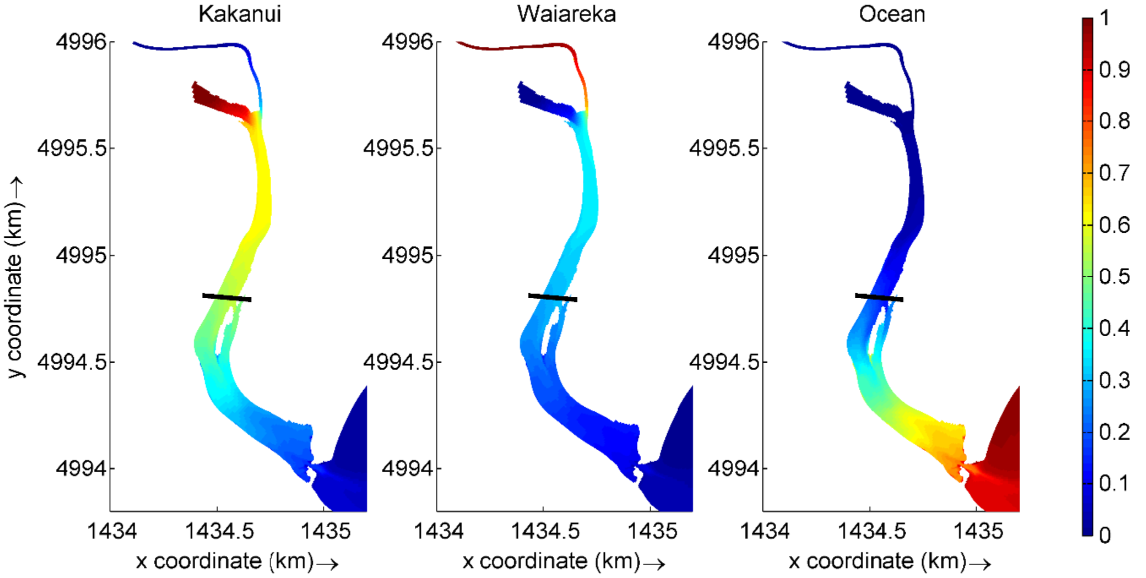

Figure 3-1: Depth- and time-averaged distributions of the fraction of water originating from Kakanui River, Waiareka Creek and the ocean. The distributions are calculated as averages of two tidal periods (24hr45min) for the surveyed mouth configuration with mean 2014-2015 summer flows (Plew and Barr 2015).

Modelling showed how the geometry of the mouth has a large influence on the water levels in the estuary and the exchange of water between estuary and ocean. When the mouth opening is large, large volumes of seawater flow into the estuary on the incoming tide, and a similar volume of mixed sea water and river water flows out on the outgoing tide. The tidal range in the estuary is large under these conditions. Riverine water from the Kakanui River and the Waiareki Stream has much higher nutrient concentrations than sea water, thus nutrient concentrations in the estuary are low when the mouth opening is large.

As the mouth constricts, which tends to happen under low flow conditions and when coastal wave action moves beach/nearshore sediments to block the entrance, there are reductions both in the tidal range, and tidal exchange of water between estuary and ocean. The composition of water inside the estuary becomes increasingly riverine, and salinity decreases while nutrient concentrations increase. The increasing nutrient concentration promotes growth of estuarine macroalgae such as *Ulva*.

The mouth can also close or partially close to the sea. An outflow over or through the beach barrier still occurs, but sea water seldom enters under such conditions. The estuary loses much or all of its tidal range, although may still display some tidal fluctuation due to backwater effects, or non-tidal water level variation due to river flow or the ability of water to flow over or through the beach barrier. The residence time of the estuary increases sufficiently to support phytoplankton blooms, resulting in visible green-brown water in the estuary. Salinity will gradually decrease over time. Eventually salinity may become too low for estuarine macroalgae to grow, but benthic freshwater algae species may accumulate.

This work showed that under low flow conditions (Kakanui River < 1000 L/s) the Waiareka Creek could become the dominant source of nitrogen to the estuary. The Waiareka Creek has very high nutrient concentrations. It has a minimum flow of 100 L/s imposed, but summer flows are more typically ~400 L/s.

The modelling and observations show that the greater the size of the estuary mouth, the better the water quality will be in the estuary. However, significant reductions in growth of algae would also require reductions in nutrient inputs from the Kakanui River and Waiareka Creek.

3.2 Influence of Wairareka Creek flows on Kakanui Estuary nutrient concentrations

3.2.1 Background

The North Otago Irrigation Company (NOIC) operate an irrigation scheme in the Kakanui estuary catchment, and one of their consent conditions is to maintain a minimum flow of 100 L/s in the Waiareka Creek. A conclusion from the previous report was that maintaining a high flow in the Waiareka Creek may be detrimental to water quality in the estuary because the Waiareka Creek has high nutrient concentrations. NOIC asked NIWA to investigate what effect reducing the minimum flow in the Waiareka Creek might have on nutrient concentrations in the estuary (Plew 2016).

Using the model developed previously, NIWA conducted 15 simulations under steady flow conditions, considering flows of 0, 20, 40, 80 and 100 L/s from the Waiareka Creek and 700 L/s from the Kakanui River (based on the observed 2014/15 summer mean flow), and three mouth configurations (closed, narrow – based on observations from the 2014/15 summer, and open).

3.2.2 Key findings

Under typical summer riverine nutrient concentrations and Kakanui River flows, at the current minimum flow of 100 L/s the Wairareka Stream is responsible for 20-27% of the estuary DIN. Reducing the flow from the Waiareka Stream could reduce nutrient concentrations in the estuary by up to 18%. However, this is unlikely to alleviate water quality issues in the estuary as the nutrient concentrations in the estuary would still be high.

3.3 Waiareka Creek: Minimum flow and water permit optimisation

3.3.1 Background

NIWA conducted further investigations for NOIC to provide information how alterations to flow in the Kakanui River and Waiareka Creek affect the Kakanui Estuary, and if mechanically opening the estuary mouth would be beneficial. This report (Plew and Duncan 2017) also considered other aspects of flow management in the Waiareka Creek that are not relevant to the estuary so are not considered further here. This study used the model developed previously, focusing on summer low flow conditions. The study considered Waiareka flows in the range 0 to 200 L/s and Kakanui River flows in the range 0 to 2000 L/s. The estuary mouth was modelled in both an open and closed state.

3.3.2 Key findings

Waiareka Creek flows

Regarding algal blooms and assuming present day nitrogen concentrations in the Waiareka are maintained, the best environmental outcome for the estuary would be if there were no flow from the Waiareka Creek to the estuary. However, this is unlikely to be an acceptable option, as instream values need to be considered for the Waiareka Creek.

At present day nutrient concentrations in both the Kakanui River and Waiareka Creek, there is no minimum flow for the Waiareka Creek that would prevent algal blooms from occurring. The present loading from the Kakanui River is sufficient to drive excess macroalgae growth (estuary-averaged DIN concentrations would drive moderate to high or high macroalgal growth rates, see Table 2-1), even if there were no flow from the Waiareka Creek.

Increasing minimum flow in the Kakanui River

Estuary nitrogen concentrations could be reduced if the concentrations in the Kakanui River were reduced. It is possible that this could be done if more of the cleaner (low nutrient concentration) water originating from higher in the catchment was retained in the river rather than being extracted for irrigation. To assess this possibility, NIWA modelled the effect of adding water to the Kakanui River assuming that most existing takes were between the upstream Clifton Falls and downstream McCones monitoring sites. Restrictions on those takes begin to come into place when the flow in the Kakanui River drops below 500 L/s. In the model, the minimum flow was increased from 500 L/s assuming that all additional water above that flow had the same nutrient concentrations as at Clifton Falls, and no additional nutrients leached into the Kakanui River. If the mouth were open, then increases in minimum flow to between 1000 L/s to 2500 L/s would be required, depending on concentrations in the river and tributaries.

Mechanical opening

Modelling shows that nutrient concentrations are higher in the estuary when the mouth is closed, so regular mechanical opening would assist in lowering nutrient concentrations and contribute to reducing macroalgal and phytoplankton growth during periods when the mouth would normally be closed. Opening the estuary mouth also reduces the flushing time of the estuary, and with estuary inflows > 500 L/s, flushing times would likely reduce sufficiently to prevent or minimise phytoplankton growth. However mechanical opening alone would not be sufficient to prevent moderate to high macroalgal growth, leading to macroalgal blooms. Reductions in nutrient loads to the estuary are also required.

4 Other reports and data

4.1 Estuary habitat surveys

A 2009 study reported the estuary was in good health (Steward 2009). However, estuary health deteriorated over subsequent years with proliferation of macroalgae along the estuary margins and in the lower estuary noted anecdotally, and in reports published in 2013 and 2015 (Ozanne and Wilson 2013; Plew and Barr 2015).

Salt Ecology conducted a synoptic survey of the Kakanui Estuary in January 2021 after anecdotal reports of fine sediment build-up and proliferation of macroalgae in the estuary (Roberts, Stevens et al. 2021). However, the 2021 survey was carried out two weeks after a significant flood in the Kakanui River, and estuary substrate was scoured down to gravel and nuisance macroalgae was absent. Salt Ecology concluded that while the estuary was in generally good health at the time of the survey, this likely represented a period of short-term improvement due to flushing of excess nutrients, sediments and macroalgae by the recent flood rather than the outcome of any improvements in the catchment.

4.2 Inflow water quality data

Several analyses of water quality in the catchment of the Kakanui Estuary have been reported (Ozanne 2012a; Ozanne 2012b; Ozanne and Wilson 2013; Mager 2021). These show seasonal fluctuations in nutrient concentrations (nitrate-nitrogen elevated during winter, DRP elevated during summer) and longitudinal trends (concentrations increasing downstream in the Kakanui catchment).

Water quality data are also publicly available via www.lawa.org.nz. The closest water monitoring sites for the inflows to the Kakanui Estuary are the Kakanui River at McCones and Waiareka Creek at Taipo Rd. A summary of water quality parameters relative to other New Zealand lowland rural river sites, and the trend over the previous 10 years obtained from LAWA (https://www.lawa.org.nz/explore-data/otago-region/river-quality/kakanui-river/) are reported in Table 4-1.

The Kakanui River provides the greatest flow and nutrient load to the estuary. All reported nitrogen variables except ammoniacal nitrogen are in the worst 50% of New Zealand rural lowland rivers, and concentrations were either likely or very likely increasing over the past 10 years. Phosphorus concentrations are in the best 25% of New Zealand rural lowland rivers, and the 10-year trend indicates that DRP concentrations are likely improving (reducing), while total phosphorus concentrations are likely degrading (increasing). Eutrophication issues in estuaries are more commonly driven by excess nitrogen from the catchment rather than phosphorus because sufficient phosphorus to prevent nutrient limitation on estuarine algae growth is usually available from ocean input, therefore the increase in nitrogen concentrations is concerning.

While the Waiareka Creek has lower flows and contributes lower nutrient loads, nutrient concentrations are considerably higher than in the Kakanui River. All reported median concentrations are in the worst (highest) 25% or 50% for New Zealand rural lowland rivers. The 10-year trends for all nitrogen variables are likely or very likely improving (reducing), but phosphorus concentrations are very likely degrading (increasing).

Table 4-1: Summary of water quality data for the Kakanui Rover at McCones and Waiareka Creek at Taipo Rd. “State” compares the 5-year median concentration to all other New Zealand lowland rural sites and shows which quartile (red: worst 25%/highest quartile, orange: worst 50%/2nd highest quartile, light green: best 50%/second lowest quartile, dark green: best 25%/lowest quartile). “10-year trend” indicates the probability that concentrations are improving (reducing over time) or increasing (red: very likely degrading = >90% confidence that concentrations are increasing, orange: likely degrading = 67% to 90% confidence that concentrations are increasing, light green: likely improving = 67% to 90% confidence that concentrations are decreasing, dark green: very likely improving = >90% confidence that concentrations are decreasing. Data were available up to Dec 2021. Retrieved from www.lawa.org.nz 10 April 2023.

	Kakanui River at McCones			Waiareka Creek at Taipo Rd		
	5-year median (mg/m^3)	State	10-year trend	5-year median (mg/m^3)	State	10-year trend
Total Nitrogen	520	Worst 50%	Very likely degrading	1440	Worst 25%	Very likely improving
Total oxidised nitrogen	350	Worst 50%	Likely degrading	610	Worst 50%	Likely improving
Dissolved inorganic nitrogen	361	Worst 50%	Likely degrading	620	Worst 50%	Very likely improving
Ammoniacal Nitrogen	2.5	Best 25%	Not assessed	9	Worst 50%	Likely improving
Nitrate Nitrogen	350	Worst 50%	Likely degrading	610	Worst 50%	Likely improving
Dissolved Reactive Phosphorus	2.5	Best 25%	Likely improving	168.5	Worst 25%	Very likely degrading
Total Phosphorus	8.5	Best 25%	Likely degrading	220	Worst 25%	Very likely degrading

Plots of nutrient concentrations over time show the general increase in most nitrogen variables (Figure 4-1). A 12-month moving average has been fitted to the data to show the trends more clearly. There is interannual variability superimposed on the long-term trend, with relatively lower concentrations in 2015 and 2020 with higher concentrations outside of those years. Plew and Duncan (2017) calculated DIN average summertime concentrations for 2014-16 that were nearly 1/3rd of the median values reported above, indicating both seasonal and interannual variability.

The nutrient concentrations can be combined with flow data to estimate monthly, seasonal or annual nutrient loads, and to see how loads trend over time; however, this work is beyond the scope of the present review.

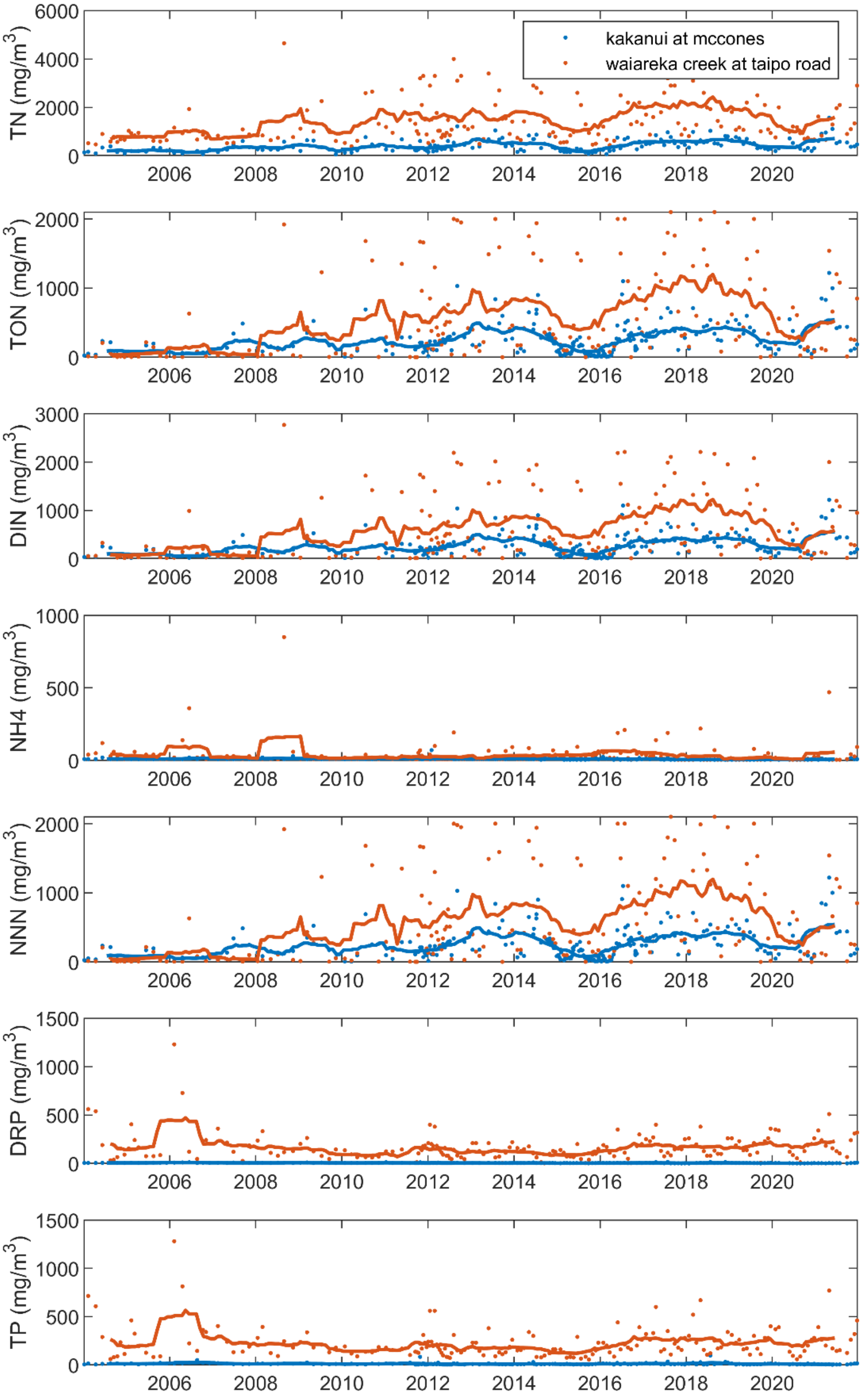

Figure 4-1: Nutrient concentrations in the Kakanui River at McCones and Waiareka Creek at Taipo Road. Data downloaded from LAWA. The lines show a 12-month moving average.

5 Summary and recommendations

5.1 Summary

The proliferation of macroalgae and phytoplankton in Kakanui Estuary is driven by excessive supply of nutrients, particularly nitrogen, from the catchment. The flushing time of the estuary also plays a role in the occurrence of phytoplankton blooms. To control algae blooms requires reducing nutrient concentrations in the estuary and reducing the flushing time of the estuary to less than ~ 3 days.

Three factors control nutrient concentrations in the estuary.

Mouth opening – when the mouth is open, the exchange of water between estuary and ocean increases, resulting in a higher portion of low-nutrient ocean water in the estuary. A wider/deeper mouth allows more exchange than a narrow opening, resulting in lower nutrient concentrations in the estuary. When the mouth is open and the estuary is tidal, the risk of phytoplankton blooms is low.

River flows – as river flows increase, the freshwater content of the estuary also increases. However, the flushing time will decrease. Increases in the minimum flow in the Kakanui River may be beneficial for controlling estuary macroalgae if the increased flow results in reduced nutrient concentrations in the Kakanui River. This assumption needs to be tested before changes in minimum flows are considered.

River nutrient concentrations – nutrient concentrations in the Kakanui River and Waiareka Creek directly affect nutrient concentrations in the estuary. At representative summer flows of 1,000 L/s and 300 L/s, respectively, and using the 5-year median concentrations from 2017 to 2021 (Table 4-1), we expect estuary-averaged DIN concentrations of ~ 280 mg/m^3, far exceeding the recommended 90 mg/m^3 target. To obtain this target would require reducing DIN concentrations in each tributary by approximately 2/3rds.

However, improvements in estuary trophic condition may be seen under load reductions less than the 2/3 figure, because the estuary is unlikely to be well mixed often (Figure 3-1). Incomplete mixing results in lower N concentrations in areas of the estuary near the ocean. Smaller reductions in N loading may therefore reduce algal growth near the estuary mouth if the greater dilution by seawater reduces N concentrations below the 70-90 mg/m^3 target. Furthermore, because macroalgal growth in the estuary's upper reaches is likely to be restricted by low salinity, high nutrient concentrations in these areas may not cause macroalgal blooms.

No single intervention is likely to prevent algal blooms in the Kakanui Estuary. Mechanical opening may alleviate phytoplankton blooms by allow the estuary to flush more rapidly and decrease nutrient concentrations in the estuary via greater dilution by seawater. However, this is unlikely to be sufficient to prevent macroalgal blooms without reductions in nitrogen inputs from the Kakanui River and Waiareka Creek.

Flow supplementation by increasing minimum flows or possibly by adding water from a low nutrient water source could assist in reducing estuary nutrient concentrations; however, the flow increases required may be large.

We note that concentrations during the 2014-2016 summer were lower than the 2017-2021 median, and close to those required to restrict algal growth. We suggest closely investigating nutrient and flow data from this period, in conjunction with knowledge of changes in land-use practices during and since that time, to determine why nutrient concentrations were low during that period and how this might be replicated in the future.

Careful on-farm irrigation management to minimise or eliminate summer drainage and reduce nutrient exports, in conjunction with other management interventions such as increases in minimum flows and mechanical opening of the estuary, could potentially improve estuarine water quality.

A more-accurate understanding of the load reductions required to reduce macroalgal growth in different areas of the estuary could be achieved by coupling an estuary mixing model (e.g., Plew and Barr 2015) with a macroalgal growth model (e.g., Dudley, Barr et al. 2022).

5.2 Recommendations

1. Analyse nutrient concentration and flow data from the Kakanui River and Waiareka Creek, in conjunction with any information available on land use changes, to determine why concentrations in the rivers vary, and whether insight can be gained into how to maintain concentrations at low values.

2. Conduct regular monitoring of the estuary to determine when and to what extent macroalgal and/or phytoplankton blooms occur. This information can then be considered along with inflow and nutrient data to refine the guideline values for nutrient reduction and monitor the effects of any interventions.

3. Install a water level recorder in the estuary to provide additional information on the tidal exchange and flushing of the estuary, aiding the interpretation of other monitoring data.

4. Consider coupling an algal growth model with the hydrodynamic model to improve estimates of the reductions in nutrient loads required to cause a meaningful reduction in macroalgal growth.

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