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Conservation
Te Papa Atawhai



NIWA
Taihoro Nukurangi



Technical Report on Vegetation Status in Waituna Lagoon: 2009–2021



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Introduction

This technical report accompanies the summary report on vegetation status in Waituna Lagoon in 2021 (de Winton and Elcock 2021). We review the lagoon conditions over the period of vegetation monitoring from 2009 to 2021 and update current vegetation status according to findings in 2021.

As background to the summary report, this technical report describes water level, mouth opening status and duration (Section 1). The report also summarises recent lagoon conditions based on monitoring of indicators of water quality carried out by Environment Southland (Section 2). We provide descriptions of monitoring methods undertaken and present summaries of data and analyses (Sections 3, 4 and 5). We briefly conclude what the findings mean for lagoon management.



1. Water Level Regime

Methods

Water level data supplied by Environment Southland from the gauge at Waghorns Road was examined to identify lagoon openings by the onset of a sudden, substantial reduction in water level. Lagoon closure was estimated from timing of subsequent, sustained increases in level. The total time period for openings was calculated, the lagoon mouth status was confirmed and the duration of that status before each vegetation monitoring event was calculated as months (one month is 30 days).

Results

The lagoon was open to the sea for a period of almost 5 months (145 days) prior to the annual monitoring of vegetation in February 2021 (Figure 1, Figure 2). Therefore, the target of three months of closed conditions prior to vegetation monitoring (Lagoon Technical Group 2013) was not achieved in 2021. This target recognises that open lagoon conditions may be detrimental to *Ruppia* development if openings persist through the main spring-summer growth period for vegetation (September to February).

The lagoon has previously been open to the sea for similar spring-summer periods lasting 3.9 to 6.2 months prior to monitoring in 2011, 2013, 2014, 2017 and 2020 (Figure 1 negative axis, Figure 2).

The lagoon was opened in late September 2020, after which the water level averaged 0.59 m less than normal up until the vegetation monitoring date (mid-February 2021), with oscillations around this value due to tidal exchanges and sea level (Figure 2).

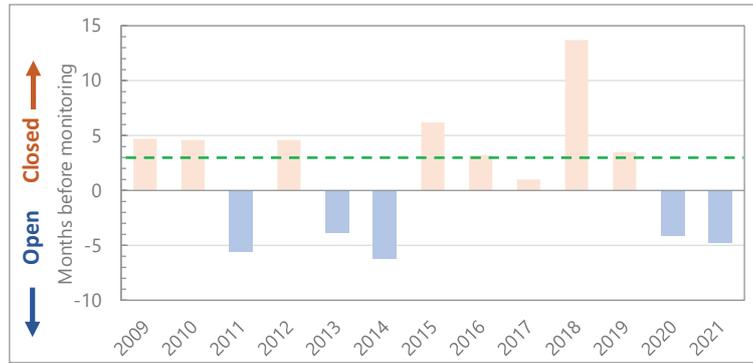


Figure 1: Diverging bar plot showing the number of months for which Waituna Lagoon was open or closed prior to monitoring (as indicated by the y axis). The dotted line indicates the ecological target of three months of lagoon closure before monitoring.

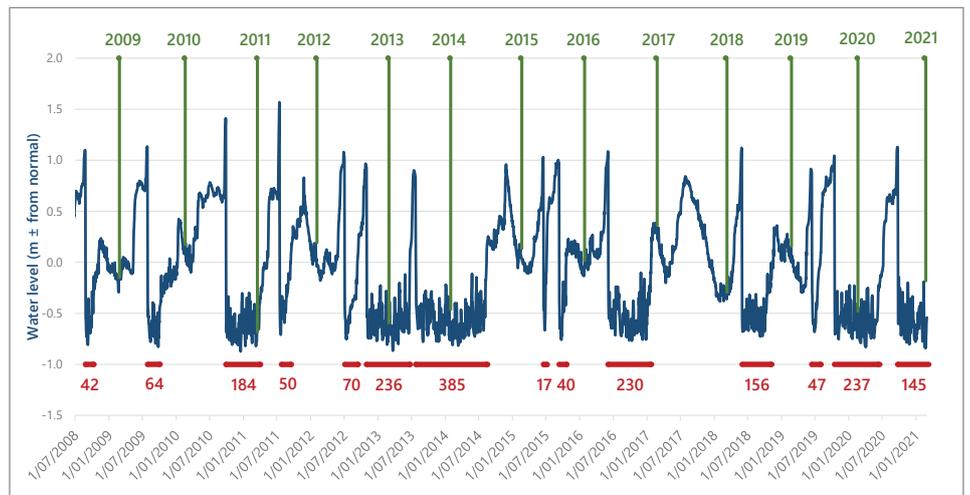


Figure 2: Plot showing the continuous water level time series for Waituna Lagoon, measured at Waghorns Road. Periods of lagoon opening are indicated by horizontal red lines. The number of days during which the lagoon was open correspond to the red numbers. Finally, the annual summer vegetation monitoring events are indicated by green vertical lines.

Discussion

The frequent artificial openings of Waituna Lagoon over the period of vegetation monitoring are very different from the natural situation (Hume et al. 2016). Usually, artificial openings are made on an annual or more frequent basis, for variable timeframes (Figure 2).

Closure of the barrier breach is unpredictable and is un-manageable, driven by high energy, predominantly wave-driven action on the mixed sand/gravel coastline. The current Consent Conditions for artificial openings of Waituna Lagoon Resource Consent (20146407-01) favours winter openings when there is opportunity for closure before the main spring/summer growth season for *Ruppia*. The late September 2020 opening of the lagoon was in response to rapidly rising lagoon levels and was permitted under the current consent conditions. However, both this September 2020 and the previous October 2019 barrier openings did not close before the annual vegetation monitoring in summer.

In contrast, in its natural state the lagoon would have been closed to the sea with openings occurring in the decadal to century time scales (Hume et al. 2016). Periods where the barrier opened would have been short-lived in comparison. Coarse substrate comprising the coastal barrier permits drainage to the sea by percolation, which would have reduced the water pressure that led to natural breaches. The barrier would have only breached naturally when sufficient pressure built from high water levels in the lagoon, and/or when severe storm waves overtopped the barrier.



2. Temporal Physico-chemical Conditions

Methods

Water quality monitoring data for Waituna Lagoon was obtained from Environment Southland from 2009 to 2021. Data from the central lagoon sampling site was used to indicate changes in conditions over time to simplify temporal patterns. Seven parameters were plotted between 2009 and 2021:

1. Chlorophyll-*a* (Chl-*a*, mg L⁻³).
2. Salinity (PSU).
3. Total Nitrogen (TN, g m⁻³).
4. Total Phosphorus (TP, g m⁻³).
5. Total Suspended Solids (TSS, g m⁻³).
6. Turbidity (NTU).
7. Temperature (°C).

Where water quality parameters were reported below detection limits, we plotted a value equal to half that detection limit. Timing and duration of lagoon openings is indicated in relation to water quality parameters.

Results

The open mouth conditions during the main 2020/21 spring/summer *Ruppia* growth season resulted in high (over 30 PSU) salinity levels recorded in the central lagoon (Figure 3a). Similar high salinities have only been recorded only when the lagoon is open. Over the 2020/21 spring/summer growth season, temperatures increased seasonally between 15 and 20°C, similar to the previous three years and reaching higher temperatures than were seen between 2016 to 2017, according to Environment Southland data (Figure 3a).

Following the September 2020 opening, the previously elevated nutrients (TP and TN) and chlorophyll-*a* concentrations (Chl-*a*) decrease, similar to patterns seen in 2018 and 2019 (Figure 3b). Peak nutrient levels recorded over the previous three years were greater than over 2016 and 2017. Measures of suspended solids and turbidity were variable following the most recent opening, in contrast to earlier decreases seen in 2019/20 (Figure 3c).



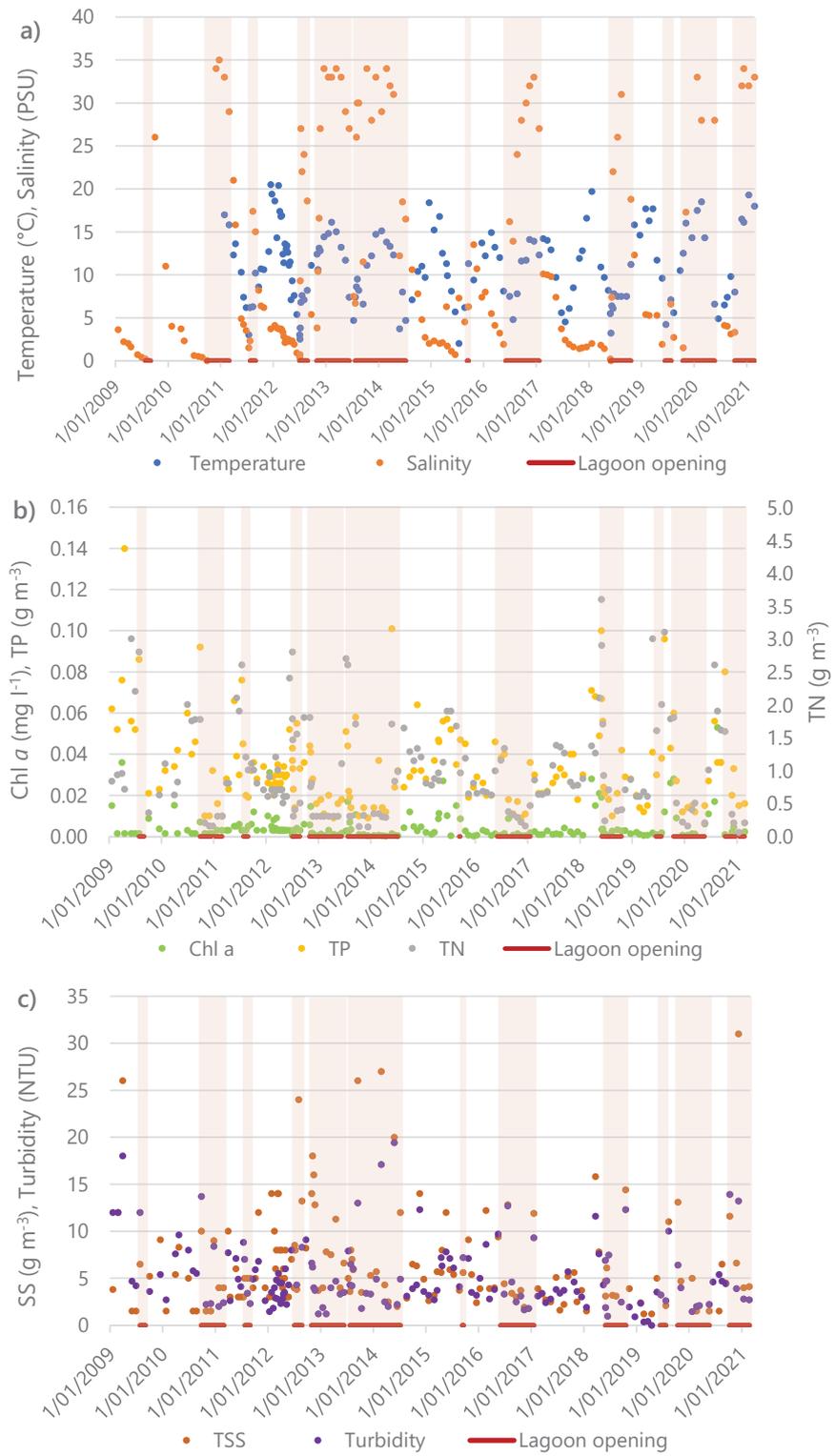


Figure 3: a) Time plots of temperature and salinity, b) Chlorophyll-*a* (Chl-*a*), total phosphorus (TP), and total nitrogen (TN), and c) Total suspended solids (TSS) and turbidity at the lagoon centre sampled over 2009 to 2021.

Discussion

The 2021 vegetation survey followed an extended lagoon opening of almost 5 months. A long (>3 month) lagoon opening is generally associated with increased salinity, decreased temperature (relative to seasonal timing), lower nitrogen and total suspended solids (de Winton and Mouton 2018a). Environment Southland data for the central lagoon after the September 2020 opening generally follow these patterns, with the exception of the relatively high temperatures recorded and temporally variable suspended solids, which could be due to tidal currents or wind action.

Mouth status and timing of lagoon openings have previously been shown to be a major driver of physico-chemical conditions in the lagoon (Schallenberg and Tyrell 2006, Schallenberg et al. 2010, Hodson 2017, de Winton and Mouton 2018a). Other patterns included strong seasonal signals in temperature, nutrients and suspended solid concentrations (de Winton and Mouton 2018a). In turn, physico-chemical conditions have been linked to the spatio-temporal patterns of the vegetation in Waituna Lagoon (Robertson and Funnell 2012, Lagoon Technical Group 2013, de Winton and Mouton 2018a).

In the following section (Section 3), we describe the physico-chemical conditions at the time of monitoring in 2021 and compare with previous annual monitoring over a range of mouth status.



3. Annual Physico-chemical Monitoring

Methods

The location of 47-48 monitoring sites is given in Figure 4. (One site could not be sampled due to the migration of the coastal spit from 2014 onwards).

At each monitoring site, measurements were made from 2009 to 2021 of:

- Water depth (m).
- Visual clarity as black disk distance (m).

A calibrated multi-sensor meter (Horiba or YSI Exo 1) measured parameters at the water surface and bottom (where depth allowed) that included:

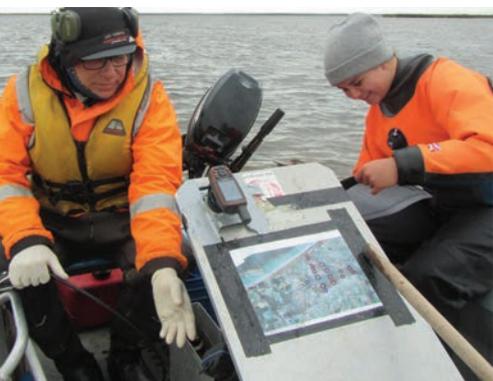
- Temperature (°C).
- Dissolved oxygen (DO, mg l⁻¹).
- Salinity (PSU).
- Turbidity (NTU).

Black disk, DO and turbidity commenced in 2011.

The surface and bottom water quality measurements were previously found to be highly correlated (Spearman $r > 0.9$, de Winton and Mouton 2018a), we therefore, employed average values for each parameter. In 2020 and 2021, where a number of sites were dry (tidally), we took water quality measurements close by. The data was then illustrated using box plots for each year (each annual monitoring event).



Figure 4: Monitoring sites in Waituna Lagoon. Transects are numbered from 1 to 10 from East to West. The numbers of each transect were allocated on ascending order from North to South.



Results

Under the open lagoon conditions at the time of the February 2021 monitoring, the average salinity was 29 PSU. Salinity values were similar to levels recorded in 2011, 2014 and 2020 (Figure 5 top), all monitoring occasions timed when the lagoon had been open for over 4 months. Seventeen sites in 2021 recorded >30 PSU, all of which were located west of transect T5 (Figure 4).

Sixteen sites were dry at the time of the 2021 monitoring. Most of these sites (twelve) were along the northern margins of the lagoon but also included the shallow southern arm close to the lagoon opening site (Figure 4). Average depth at monitoring sites in February 2021 (0.27 m) was the lowest of all monitoring years, being less than values recorded during previous monitoring during open lagoon conditions in 2011, 2013, 2014 and 2020 (Figure 5 middle). The remainder of monitoring events were deeper due to closed lagoon conditions, although 2018 also had relatively low water levels (Figure 5 middle) due to a drought year in the region rather than open mouth status.

Water temperatures recorded for lagoon waters during the 2021 monitoring event (average 16.7°C) were lower than recorded in 2013, 2015, 2017 and 2020 but higher than 2009 to 2012 (Figure 5 bottom).

An average DO of 8.8 mg l⁻¹ recorded during monitoring in 2021 was similar to 2013, 2014 and 2020 (Figure 6 top). The 2021 minimum DO of 7.8 mg l⁻¹ was well above the threshold of 5 mg l⁻¹ that is considered necessary for healthy aquatic life. Over 75% of sites in 2021 recorded DO values >85%, which indicates well oxygenated conditions.

An average turbidity of 11.2 NTU during the 2021 monitoring, is similar to 2013 and 2015–2019 but lower than 2011, 2012, 2014 and 2020 (Figure 6 middle). However, the black disk measurement averaged only 0.67 m in 2021 and was amongst the lowest values recorded, similar to 2011, 2012, 2018 and 2020 (Figure 6 bottom). This may reflect the very shallow depths of many sites in 2021 and observed resuspension of sediment. Water colour (dissolved organic carbon) can also reduce water clarity. Also notable in 2021 was the occurrence of strong currents at some central sites (in keeping with low and tidally influenced lagoon levels) that resulted in observed re-suspension of macroalgae and other drift debris that would have contributed to low visual clarity (black disk). These influences would not necessarily be detected as turbidity (NTU).



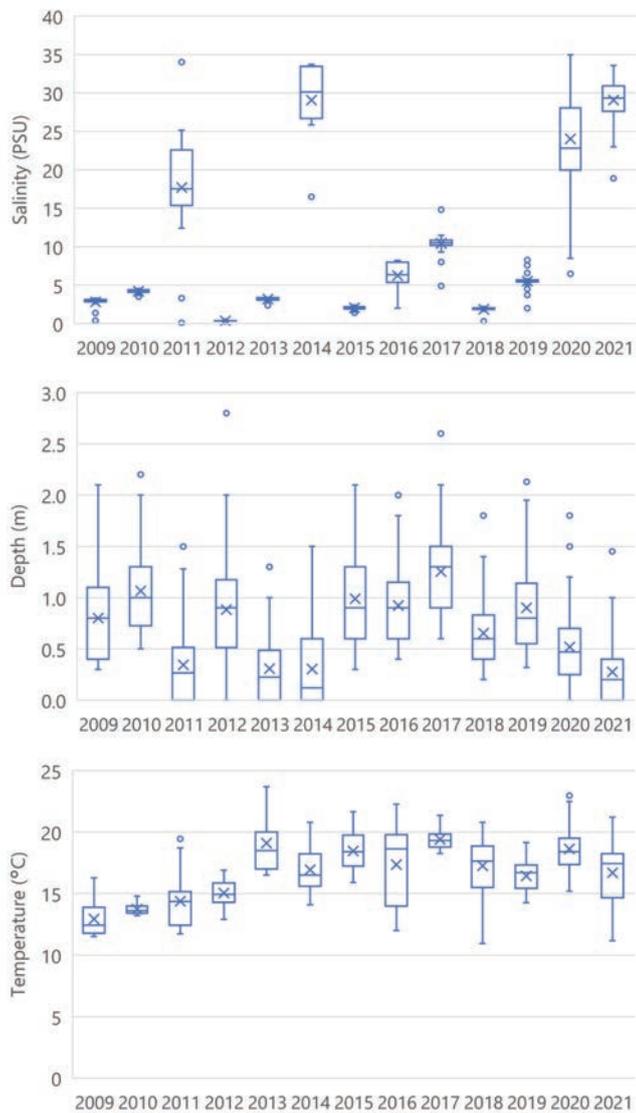


Figure 5: Box and whisker plots of salinity (top), depth (middle) and temperature (bottom) over all monitoring years. (n= 48 or 47).

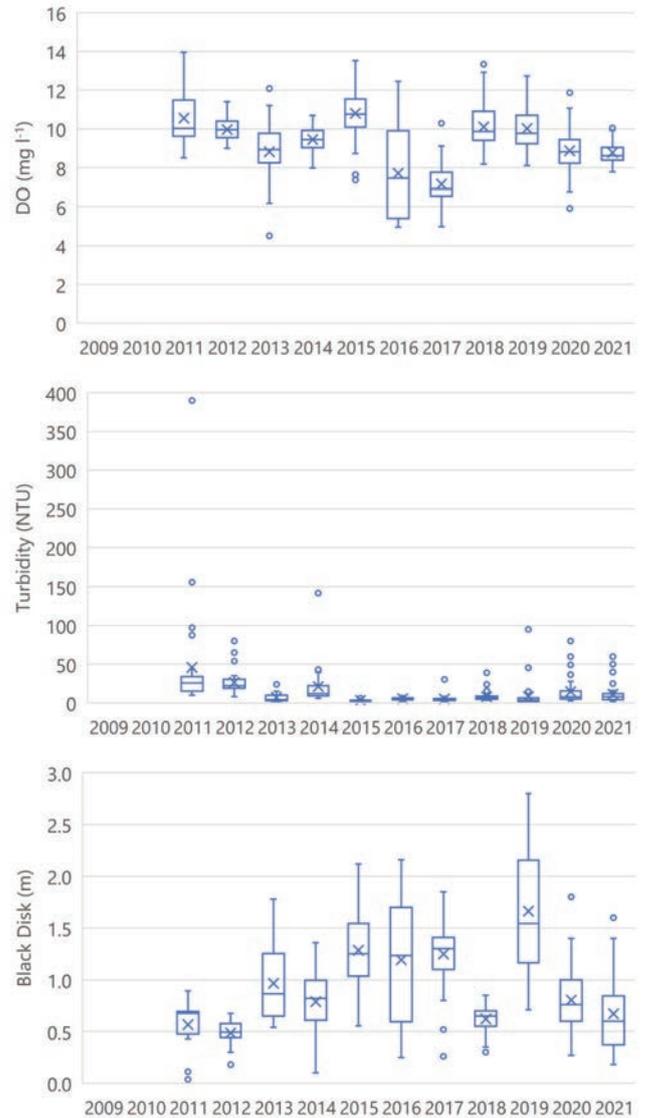
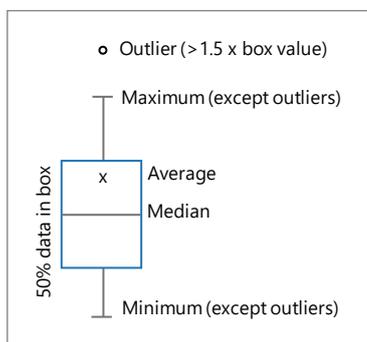


Figure 6: Box and whisker plots of DO (top), turbidity (middle) and black disk (bottom) at the monitoring sites (n= 48 or 47), from 2011 to 2021.



The legend shows features that are plotted on the graphs above.

Discussion

Physico-chemical conditions at the time of the annual vegetation monitoring reflect whether the lagoon is open or closed and also reflect the prior mouth status. However, we note that measurements taken during the vegetation monitoring event are ‘snap-shot’ only and are likely to be influenced by short-term meteorological events in addition to mouth status and seasonality. For instance, water temperature from NIWA monitoring in 2021 suggested cooler conditions than 2020, but Environment Southland data (Section 2) indicated higher water temperatures.

The 2021 monitoring event showed increased salinity, in keeping with an open mouth status, but black disk was lower than expected under an open lagoon scenario of decreased total suspended solids (de Winton and Mouton 2018a). Observed re-suspended debris influencing the light climate for *Ruppia* growth due to tidal cycle currents in addition to measurements of suspended fines (NTU) are likely to be reflected in the low black disk measurements recorded at this time. Water clarity would interact with depth to determine the light climate for *Ruppia* and growth of other macrophytes, so low water levels in 2021 may have compensated for a low light transmission through the water column.



4. Sediment Characteristics

Methods

At each monitoring site (Figure 4), four replicate samples 15 x 15 cm and 6 cm deep were cut from the lake-bed, using a flat based garden hoe, and carefully lifted to the surface.

Each sample was assessed for:

- Substrate type (described as combinations of soft or firm mud, sand and gravel), was assigned a score from 1 to 10 describing increasing hardness.
- Depth (cm) to a blackened layer in the substrate, which indicates sulphide accumulation (elsewhere referred to as the redox potential discontinuity layer, Stevens and Robertson 2007). Depth was categorised into five classes: surface, >0–2, 2–4, >4 cm and layer not recorded.

Results

Sediment composition in 2021 showed a similar low proportion of softer/finer substrates (categories 1 to 3) to monitoring events recorded in 2012–2014, 2016, 2018 and 2020 (Figure 7). By contrast, substrates in 2009 to 2011, 2015, 2017 and 2019 were softer/finer (Figure 7). Substrates characterised by firm sand (categories 7 and 8, Figure 7), comprised a higher proportion (>30% samples) over 2012 to 2017, 2019 and 2021.

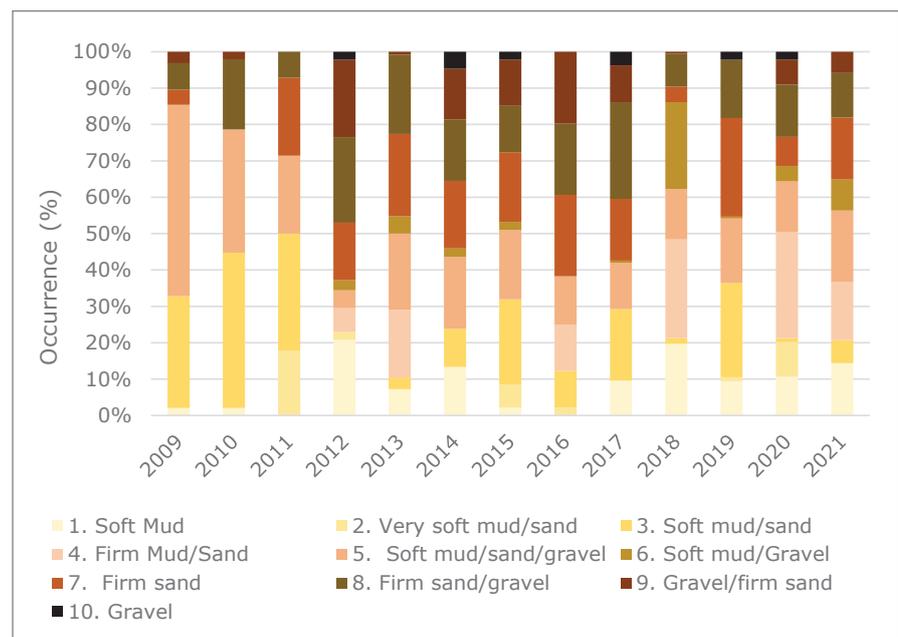


Figure 7: Bar plot illustrating the composition in substrate type (% occurrence), recorded during each of the annual monitoring surveys. Substrate types are numbered from softer to harder.



Only 7% of substrate samples recorded a blackened layer at the surface in 2021 (Figure 8). Most of these samples comprised soft mud. By contrast, 71% of samples did not record a blackened layer as it was either not present or positioned deeper than the sample (4-6 cm). This absence of a blackened layer is similar to the 2014 results, which also followed an extended period of lagoon opening. As observed in 2020 (after an extended opening), a number of samples (11%) in 2021 had a mottled appearance where a distinct blackened layer could not be discerned.

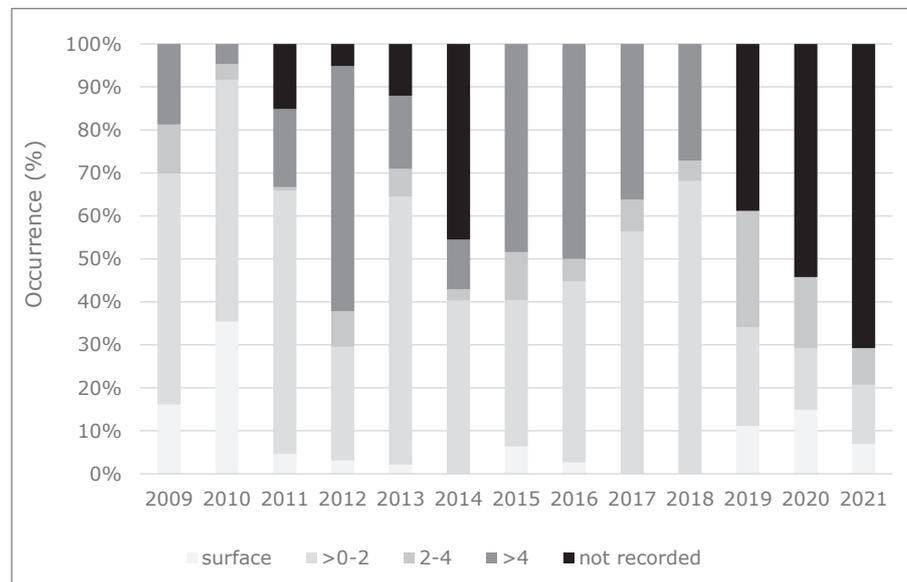


Figure 8: Substrate depth to a blackened layer shown as occurrence (% records) for five incremental depth categories.

Discussion

A greater proportion of firm sand substrates were noted in 2021. This is keeping with known associated intrusions of marine sand after extended openings (Larkin 2013). It was also noted that some sites near the opening location had been modified by sandbank deposition. Harder substrates are associated with a better ecological condition (Stevens and Robertson 2007), but sand infilling and burial of macrophytes may be an additional negative impact of long openings.

Blackened layers near the sediment surface are thought to indicate lower oxygen status and increased risk of nutrient release or toxic reduced substances accumulating in the substrates. The reduced occurrence of a blackened layer in the 2021 sediment samples continues the trend seen in 2020 and suggests the sediment surface is more oxygenated and 'healthier'.



5. Vegetation Development

Methods

At each site (Figure 4), four replicate samples 15 x 15 cm and 6 cm deep were cut from the sediment, using a flat based garden hoe, and carefully lifted to the surface. Each sample was assessed for:

- Presence of submerged plant species and/or macroalgae types and their cover as %. Where covers were previously recorded as a cover score range¹ in 2009 and 2010, these were translated to a mid-point value.
- Height of each macrophyte species present (cm). Where heights were previously recorded as a range² in 2009 and 2010, these were translated to maximum value of the range.
- Life stage of *Ruppia* spp. (vegetative, flowering or post flowering).

Cover and height of *Ruppia* was averaged across the four replicates at each site. Biomass index for *Ruppia* was calculated as the product of average cover and height at each site.

From 2013 onwards, macrophyte observations were also made at each site by snorkel/SCUBA diver within a circular area of 10 m diameter. The maximum and average cover scores and height were recorded for each macrophyte species and macroalgae present.

Results

Vegetation composition

No vegetation (plants or macroalgae) was recorded at sixteen monitoring sites, based on the hoe samples in 2021 (Figure 9), with six of these sites being dry at the time of monitoring. The non-vegetated sites that were immersed were all in the south-western half of the lagoon (T 7.3–7.7, 8.3–8.5, 9.2 and 10.2, Figure 4). Sites without any vegetation were fewer than previous years when the lagoon had similarly been open for c. 4-6 months in 2011 (29 sites), 2013 (26 sites) and 2014 (32 sites). However, these years had a much lower contribution by macroalgae (Figure 9).

Ruppia polycarpa was the most widespread submerged plant recorded in the hoe samples in 2021 but was present at only eleven sites. *R. megacarpa* was recorded at three sites, none of which recorded *R. polycarpa* and were restricted to the eastern lagoon (T 1.1, 4.3 and 4.5, Figure 4). Overall sites with *Ruppia* comprised less than half the number recorded in 2020. Correspondingly, *Ruppia* species in 2021 together formed a lower contribution to vegetation composition than recent years of 2015 to 2020 and was similar to previous extended opening years of 2011 and 2014 (Figure 9).



Recorded diversity of other submerged plants in the hoe samples was low in 2021, similar to 2020 (Figure 9). The charophyte *Lamprothamnium macropogon* was present at two sites in the eastern lagoon. This charophyte has been more conspicuous in the years that the lagoon has been closed including 2012, 2015-2016 and 2018-19 (Figure 9). The amphibious turf plant *Lilaeopsis novae-zelandiae* was recorded at one dry site in 2021 (Figure 9). The freshwater macrophyte *Myriophyllum triphyllum* was not recorded in 2021.

Macroalgae formed a major component of the vegetation in 2021 (Figure 9) but to a lesser extent than in 2020 based on hoe samples. Again, macroalgae were dominated by filamentous green species (17 sites) and *Ulva intestinalis* (13 sites), but overall species composition showed stronger brackish/marine associations than in 2020. Filamentous green algae were mainly comprised of the genus *Cladophora* but were sometimes co-dominated by *Rhizoclonium*, *Microspora* or cf. *Draparnaldia*.

¹ 1 = 1–5%, 2 = 5–10%, 3 = 10–20%, 4 = 20–50%, 5 = 50–80%, 6 = 80–100%

² <5 cm, 5–15 cm, 15–30 cm, 30–50 cm, 50–80 cm, 80–100 cm



This filamentous green algal group showed a slight increase in occurrence relative to *Ulva* in 2021. These two categories of macroalgae became more prominent components of vegetation over 2015–2017 and 2019 onwards (Figure 9). It was also common to see marine red macroalgae in 2021, most frequently cf. *Compsopogon*, while a ‘filamentous brown’ macroalgae in the drift was dominated by the diatom *Licmophora*.

The diatom *Bachelotia antillarum* has not been prominent since 2014 (Figure 9). In contrast to recent years, *Bachelotia* was noted as widespread in 2009 and 2010 (Robertson and Stevens 2009, Stevens and Robertson 2010). However, the hoe did not sample this alga successfully and results were not able to be adequately quantified or included in the results plotted in Figure 9.

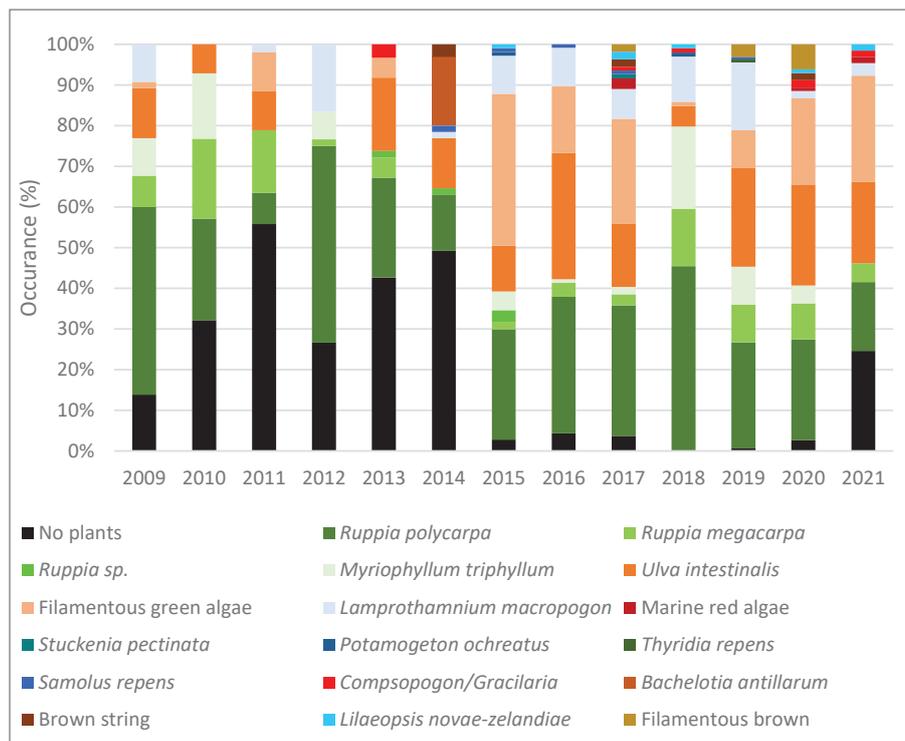


Figure 9: Vegetation composition shown as relative frequency of occurrence (sites recorded) for species or vegetation groups.

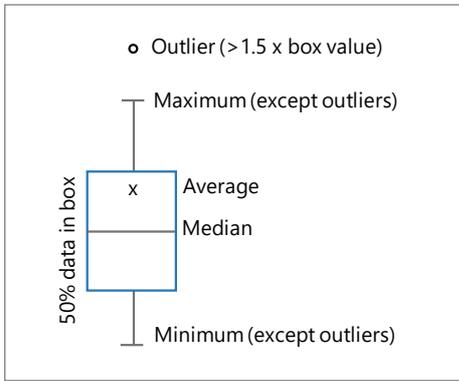
Ruppia abundance



Average *Ruppia* covers measured by the hoe method in 2021 were 2.7%, which at <10% is amongst the lowest previously recorded years of 2011–2014, 2017 and 2020 (Figure 10a). The highest *Ruppia* covers of ≥ 20 -80% were exclusively associated with *R. megacarpa* in 2021. Previously, *R. megacarpa* was also disproportionately represented in hoe samples that recorded high covers ($\geq 80\%$).

The average height of *Ruppia* in 2021 measured from hoe samples was 12.8 cm. This is similar to the lowest previously recorded years of 2011–2014 and 2020. All recorded *Ruppia* heights over 20 cm were represented by *R. megacarpa* in 2021, which comprised the three taller outliers in the graph (Figure 10b). *Ruppia megacarpa* has been disproportionately represented amongst the taller height records in all monitoring events to date.

‘Biomass index’ is calculated as the product of average cover x height at sites using the hoe method and is a proxy for biomass in *Ruppia*. The average biomass index in 2021 at 103 was similar to 2011–2014, 2017 and 2020 (Figure 10c). In contrast, average biomass index exceeded 1000 in 2015–2016 and 2018–2019 (Figure 10c). As common in years before, high outliers for biomass index in 2021 represent sites with *R. megacarpa*.



Biomass index' is calculated as the product of average cover times height at sites using the hoe method and is a proxy for biomass in *Ruppia*. The average biomass index in 2021 at 103 was similar to 2011–2014, 2017 and 2020 (Figure 10c). In contrast, average biomass index exceeded 1000 in 2015–2016 and 2018–2019 (Figure 10c). As common in years before, high outliers for biomass index in 2021 represent sites with *R. megacarpa*.

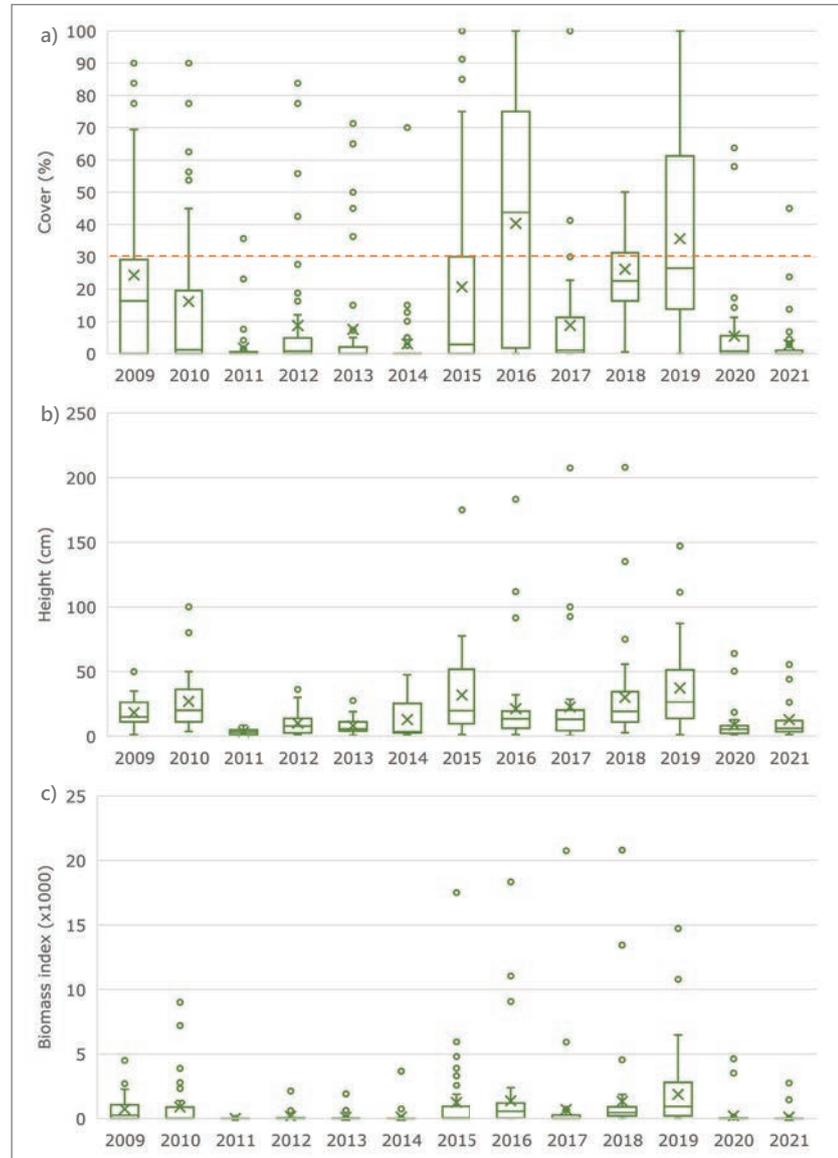


Figure 10: Box and whisker plots of *Ruppia* cover a), height b) and derived biomass index c) over monitoring years, as an average of measurements at monitoring sites (n= 48 or 47). Dotted line represents the lagoon-wide target for *Ruppia* cover of 30% identified by the Lagoon Technical Group (2013).



Diver observations within a 10 m diameter area at each site show some correlation with *Ruppia* covers and heights sampled with the hoe method since 2013 (Figure 11 top). However, observations at the larger spatial scale were more likely to detect *Ruppia* where plant covers were low or patchy. In 2021, the average lagoon-wide cover of *Ruppia* estimated from diver observations was 4.3% (not much greater than the 2.7% cover measured using the hoe method). Diver observations similarly showed low average *Ruppia* covers of less than 12% for monitoring years 2013, 2014, 2017 and 2020, with covers exceeding 30% for the years 2015, 2016, 2018 and 2019. Average height of *Ruppia* estimated by divers in 2021 was 19.6 cm, compared to 12.8 cm measured using the hoe method, in keeping with diver method tendency to report taller plants over the larger assessed area (Figure 11 bottom).

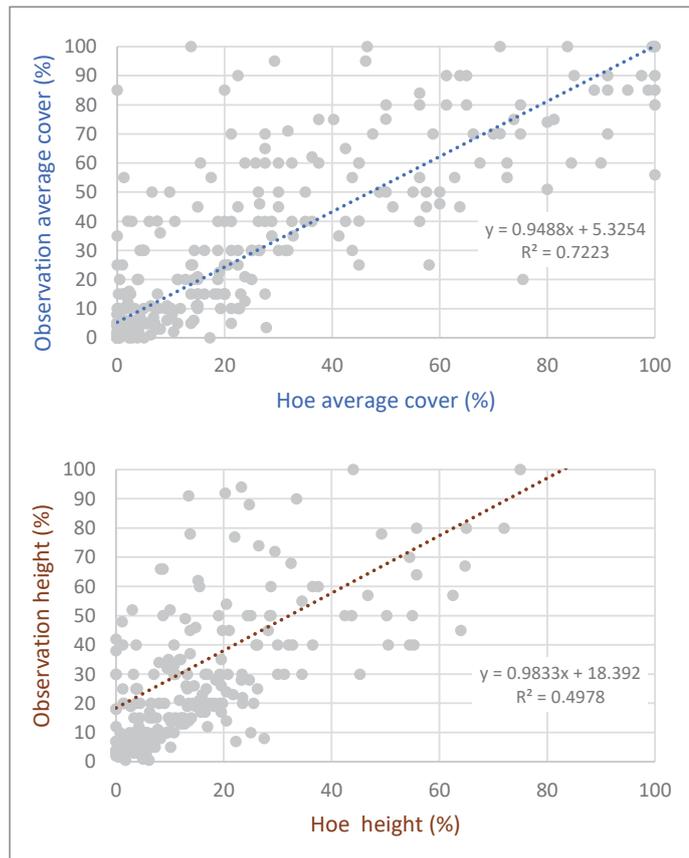


Figure 11: Relationship between *Ruppia* cover (top) and height (bottom) estimated from hoe samples and diver observations within a 10 m diameter area at each site.

Ruppia life-stage

Only *R. megacarpa* was recorded as flowering or post flowering at two sites in 2021. This reproductive status at just 6% of hoe observations for *Ruppia* is amongst the lowest recorded, similar to 2011, 2013-2014, 2017 and 2020 (Figure 12) when the lagoon had also been open for much of the *Ruppia* spring-summer growth period.

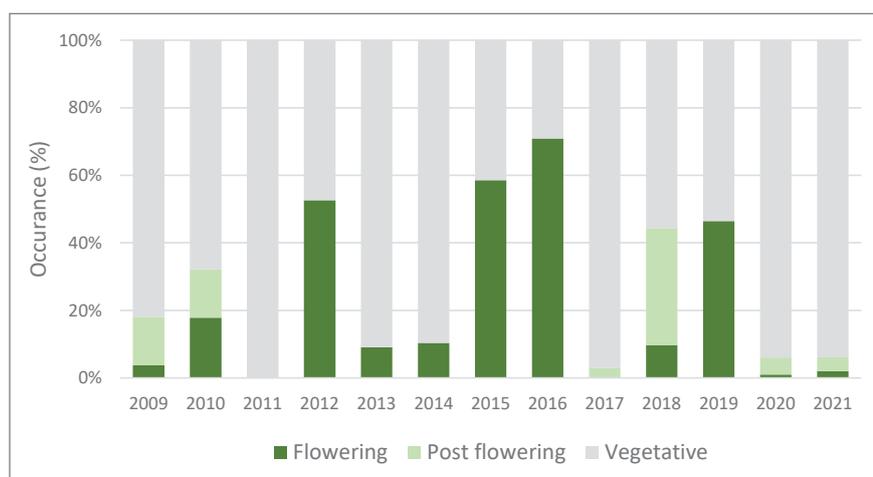


Figure 12: Life-stage category of *Ruppia* species across monitoring years as a proportion of records.



Macroalgae beds can 'lift-off' and grow as a surface mat in still, warm weather.

Macroalgal cover

In 2021, the lagoon-wide average cover for macroalgae was 14.8% according to the hoe method (Figure 13). This was a lower macroalgae cover than the average values of 25–66% recorded over 2015–2016 and 2019–2020 (Figure 13). Macroalgae levels based on the hoe method in 2021 were substantially higher on average than recorded in 2009–2014 and 2018 (Figure 13). Notably in 2021, the highest macroalgal covers from the hoe method predominated amongst western lagoon sites (T8–T10), comprising six out of the seven sites that recorded average macroalgae covers >50%. Note that macroalgae could exceed 100% cover at some sites due to combinations of benthic, epiphytic, and floating growths of different algal types (Figure 13).

However, issues with the hoe method of estimating macroalgae cover were more apparent under the field conditions in 2021. Previously, issues with dislodging of algal cover when the hoe is retrieved to the surface have been noted (Robertson and Stevens 2009, Stevens and Robertson 2010). As well as this continuing problem, at a number of sites in 2021 there were strong tidal currents associated with the very low lagoon levels, which meant substantial macroalgal biomass was suspended as drift in the water column and could not be estimated accurately as cover.

There remains a weak correlation (all monitoring years) between macroalgal cover estimate by hoe samples and overall covers observed by divers (Figure 14). Diver observations provided a higher lagoon-wide estimate of macroalgae cover, than the hoe method of 26.6% in 2021, but because of the issues with macroalgae drift, this was still likely to be an underestimate of macroalgal abundance in 2021.

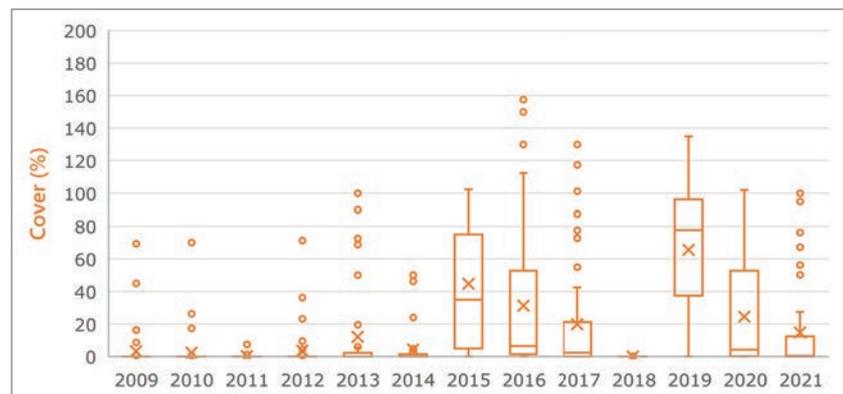
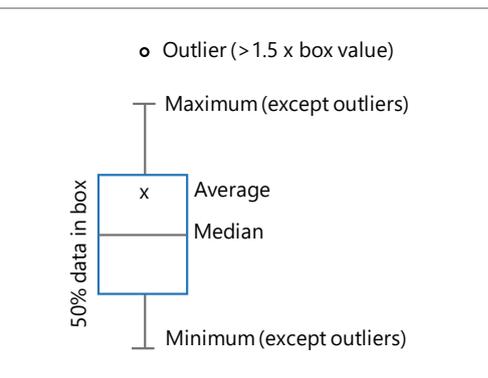


Figure 13: Box and whisker plots of macroalgae cover over monitoring years as an average of hoe measurements at monitoring sites (n= 48 or 47).

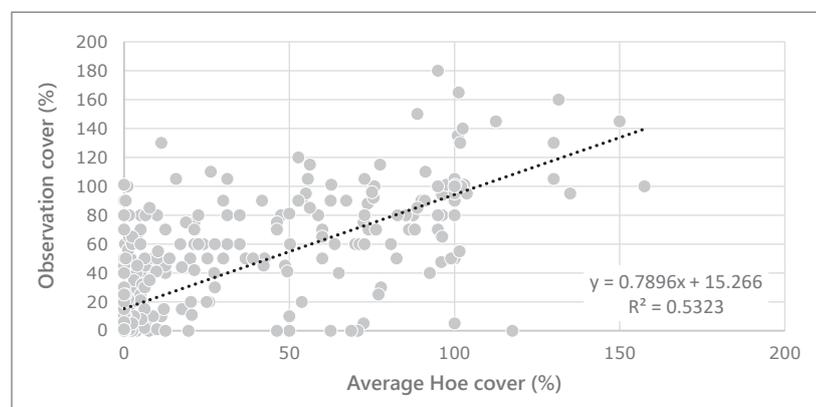


Figure 14: Relationship between macroalgal percentage cover estimated from hoe samples and diver observations within a 10 m diameter area at each site.



Discussion

Monitoring in 2021 showed further reductions in *Ruppia* development from those documented in 2020, when an earlier, extended lagoon opening occurred over the main growth season for *Ruppia* (September to February). Although in 2020, *Ruppia* remained distributed widely across the lagoon (68% of sites) and was considered well positioned to recover, the second subsequent poor season has resulted in half the site frequency in 2021 (30% of sites) and a retraction in plant distribution to the eastern sector of the lagoon. *R. megacarpa*, an important 'ecosystem engineer', underwent an even greater retraction to 1/3rd of previous 2020 sites (reduced to three sites). This result illustrates the cumulative effect of poor (open) conditions during the prime *Ruppia* growing period. Conversely, two or more consecutive closed growth periods (e.g., 2015-16 and 2018-2019) have previously led to substantial *Ruppia* expansion. The indications of *Ruppia* reductions in 2021 were shown by both survey methods. As discussed, the continuation of additional diver observations is useful where patchy vegetation distribution means small scale hoe sampling may under-represent plant abundance.

In keeping with previous observations, a poor growth season caused by an extended spring-summer lagoon opening resulted in low reproduction success for *Ruppia* in 2021. This is the second consecutive year with low reproductive success. The limited growth reserves of small plants for reproductive shoots to attain the water surface under open lagoon conditions may be responsible for lack of successful flowering and fruiting. Elsewhere flower abundance has been linked to above ground biomass of *Ruppia* species (Santamaría et al. 1995) and flowers must reach the water surface for successful pollination. Poor fertility under high salinity conditions has also been noted for *Ruppia* species in Australian wetlands (Sim et al. 2006).

Previous investigations suggest the seed bank for *Ruppia* species is perennial (de Winton and Mouton 2018a) and would provide an important means of vegetation recovery following severe perturbation. However, seed longevity has not been determined. In 2021, as in 2020, we observed germinating seed of *R. megacarpa* seed during the survey.

Difficulties in estimating macroalgal biomass, particularly incomplete benthic sampling using the hoe method, are likely to have led to an under-estimate of abundance in 2021. Accordingly, it appears that 2021, like 2020, has a higher macroalgal development than has occurred under previous years of an extended lagoon opening.

The data over a number of years does not support lagoon mouth status as a strong driver of macroalgae development. A shorter response time of macroalgae populations than *Ruppia* to ambient lagoon conditions may explain this. Instead macroalgae are more likely to respond to short-term meteorological events and their influence on nutrient loading and temperature conditions in the lagoon, in addition to mouth status. Moreover, observations of the mobility of drift macroalgal biomass in 2021 suggests possible disconnects between macroalgae growth source and accumulations. Macroalgal abundance is not an obvious driver of *Ruppia* declines, with mouth status being a stronger signal for *Ruppia* development. Although impacts on *Ruppia* can be mediated by macroalgae shading, this would be greater where algal mats develop at the water surface due to warm, still conditions.





Informing Future Lagoon Management and Research

Ruppia-dominated submerged vegetation at Waituna Lagoon is valued because of ecological benefits provided, especially the flow-on influences on water quality and habitat structure. The *Ruppia* community can also be valued in its own right, being unique to coastal lagoons, hapua and lakes and having been lost from many such systems in New Zealand. For instance, *R. megacarpa* is largely restricted to coastal systems and limited inland waterbodies with geothermal influences. It is designated At Risk – Nationally Uncommon under the New Zealand Threat Classification System (de Lange et al. 2018). This species is also considered a strong ‘ecosystem engineer’. *Ruppia polycarpa* is widespread in freshwater, but only dominates vegetation in coastal systems where salinity tolerance gives it a competitive edge over other freshwater plants.

The long-term dataset of thirteen annual (summer) vegetation surveys at Waituna Lagoon provides strong evidence for the deleterious impact of a sustained open lagoon on *Ruppia* development, distribution and reproduction during the main growth season of September to February. The dataset includes five monitoring events when the lagoon had been open for over three months prior to monitoring (2011, 2013 and 2014, 2020 and 2021) and one monitoring event when the lagoon had been closed for just one month prior (2017). Impacts appear greater (e.g., % cover reduction) in the second year of consecutive years of open lagoon conditions over the main *Ruppia* growth season. *Ruppia megacarpa* was more greatly impacted by extended and consecutive spring/summer lagoon openings than *R. polycarpa*. In 2021, *R. megacarpa* was restricted to a few refuge sites in the eastern lagoon.

Open lagoon conditions that influence *Ruppia* abundance include increased salinity and low lagoon levels. High salinity is shown to reduce *Ruppia* growth rates (Gerbeaux 1989). Concurrently, greater losses of plant biomass under open lagoon conditions are expected from tidal currents, surges, wave action, burial from substrate mobilisation, and increased waterfowl grazing accessibility. These losses relative to lower growth rates probably drive



Ruppia dynamics in the open lagoon. Salinity alone is unlikely to cause significant *Ruppia* losses. Elsewhere *Ruppia* species can persist under even hypersaline conditions (Sinclair et al. 2020), and dieback of *Ruppia* was not seen during observations just 18 days after a winter opening at Waituna Lagoon (de Winton and Mouton 2018b). Light availability for plant growth is another potential factor, but light levels for plants should be higher during openings due to reduced water depth, together with likely decreased algal biomass and total suspended solids from flushing (de Winton and Mouton 2018a).

Recovery of *Ruppia* populations proceeds with a closed lagoon over the main growth season, with some evidence of additional recovery (e.g., % cover) over consecutive closed years (2015 and 2016, 2018 and 2019). Observed recovery has previously involved both vegetative expansion and seed germination. Seed banks provide the means of recolonization when *Ruppia* distribution has retracted, but seed germination would be expected to result in slower biomass recovery than where vegetative expansion is possible. Seed germination will be important following the recent 2021 extended opening, as *Ruppia* plants have been altogether lost from the south-western sector of the lagoon. Reduced reproductive success of *Ruppia* over 2020 and 2021 summers are of concern for the replenishment of the seed bank. Although there is evidence that the seed bank is perennial at Waituna Lagoon (de Winton and Mouton 2018b), seed longevity is unknown, and losses are expected in the form of germination resulting in unsuccessful establishment. Inadequate recharging of seed banks after poor flowering success in a related *Ruppia* species led to slowed population recovery (Sinclair et al. 2020).

Freshwater plants either appear in the lagoon (e.g., *Potamogeton ochreatus*) or expand (e.g., *Myriophyllum triphyllum*) only in monitoring events when the lagoon closure has persisted for some months prior. Subsequent years with openings have led to reductions in these species, in keeping other findings that increasing salinity favours *Ruppia* species over milfoil species (Hillman and La Peyre 2019). Under the current opening regime, it is unlikely that freshwater macrophytes will take over from the salinity tolerant *Ruppia* species.

In contrast to the response patterns of *Ruppia* to managed openings at Waituna Lagoon, patterns in the development of macroalgae are less clear. Some of this disconnect may relate to shorter response timeframes by macroalgae communities and the inadequacy of current sampling frequency and methods. Key drivers for macroalgae are believed to include nutrient availability and temperature. Summer monitoring over 2020 and 2021 suggested macroalgal biomass remained relatively high, despite expected flushing of nutrients from the lagoon under open conditions. Higher algal biomass has been a feature of summer monitoring since 2015, with exception of low macroalgae in the drought year of 2018. It may be that macroalgae abundance built up by 2019 has been able to persist under the subsequent two summers of open lagoon conditions. For example, macroalgal mats that accumulate on sediment surfaces in shallow environments may be sustained by the release of porewater nutrients into overlying waters (McGlathery et al. 1997).

Sediment condition had apparently further improved in 2021, which constituted a second consecutive extended opening before monitoring. Fine sediment appeared to have been redistributed/flushed/processed, or alternatively harder substrate introduced, and sulphide horizons were deeper (or absent).

Findings to date point to the need to limit consecutive years of spring/summer openings to preserve significant submerged vegetation influences. However, they generally show *Ruppia* has the capacity to rapidly recover from short or infrequent openings under current water level and water quality conditions. There is more uncertainty on what drives annual macroalgal development and it may be the current annual 'snapshot' surveys are not sufficient to determine responses of this community.

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