Department of Conservation
Te Papa Atawhai

NIWA
Taihoro Nukurangi





Technical Report on Vegetation Status in Waituna Lagoon: 2009–2023

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Contents

Introduction

This technical report accompanies the summary report on vegetation status in Waituna Lagoon in 2023 (de Winton et al. 2023). We review the lagoon conditions over the period of vegetation monitoring from 2009 to 2023. Specifically, we assess changes in vegetation status over time with water level management, comprising artificial opening to the sea for drainage, and the unpredictable, natural process of lagoon barrier closure.

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). Finally, 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

At the time of the annual monitoring of vegetation in 2023 (23–26 January 2023), the lagoon had been closed to the sea for 500 days (Figure 1, Figure 2). This closed period incorporated two consecutive spring-summer growth seasons for *Ruppia* and is the longest closed period in the 15-year dataset. Therefore, the target of three months of closed conditions prior to vegetation monitoring (Lagoon Technical Group 2013) was achieved in 2023. This target was also achieved in eight of the previous 14 monitoring years, including 2022 (Figure 1, Figure 2).

The previous lagoon opening before the 2023 monitoring was in September 2021, with this closing within days. Immediately before the 2023 monitoring, water level had mostly remained above normal level (average +0.5 m) for the previous 240 days. This followed a prolonged period (267 days) following the last lagoon opening when water levels were below normal levels (average -0.5 m) during closed lagoon conditions, with these low levels being a result of drought conditions in Southland. Water levels over the three months before the 2023 sampling dropped steadily from about 0.90 m from above normal to 0.3 m below normal. All monitoring sites were underwater at the time of the 2023 survey. This followed the 2022 year where drought conditions meant approximately 15% of monitored sites were dry or nearly dry.

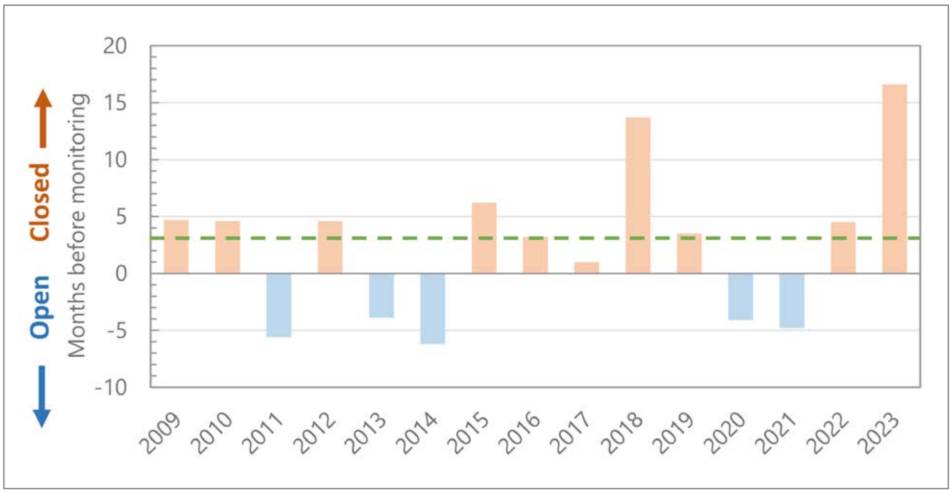


Figure 1: Diverging bar plot showing the number of months for which Waituna Lagoon was open or closed prior to monitoring (as indicated by the y axis). The dotted line indicates the ecological target of three months of lagoon closure before monitoring.

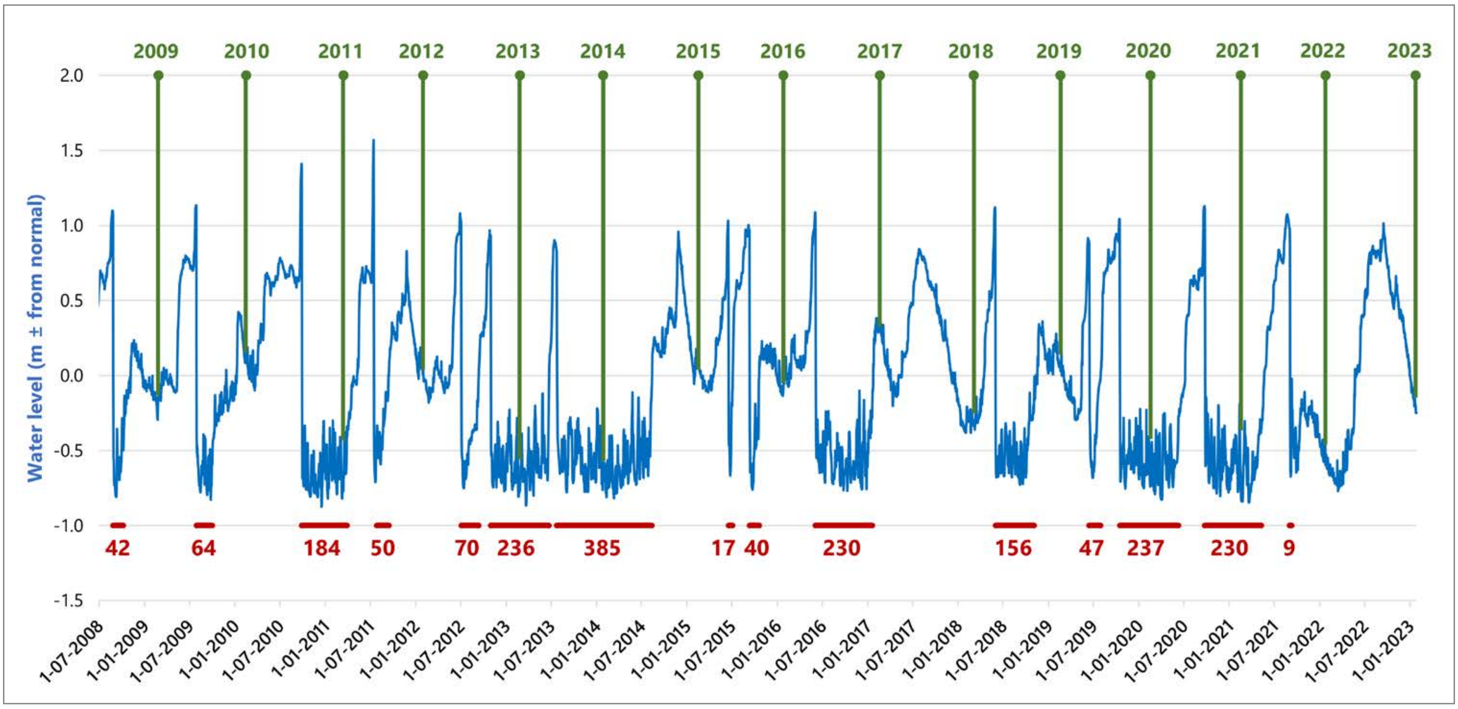


Figure 2: Plot showing the continuous water level time series for Waituna Lagoon, measured at Waghorn Road. Water level of 0 m on the graph is equivalent to 1.2 m a.s.l. Periods of lagoon opening are indicated by horizontal red lines. The number of days during which the lagoon was open correspond to the red numbers. Finally, the annual summer vegetation monitoring events are indicated by green vertical lines.

Discussion

Waituna Lagoon has been mechanically opened to the sea for land drainage purposes approximately once a year over the last c. 100 years. Lagoon closure is a natural process, driven by the effect of tides, currents and waves on redistribution of the gravel in the coastal barrier.

The last opening prior to the 2023 monitoring was in early September 2021 under conditions of the Resource Consent (20146407-01). Consent conditions permitted opening at a level of 2 m above sea level (a.s.l.) in winter, favouring early openings where there was opportunity for closure before the main spring/summer growth season for *Ruppia*. Openings over spring to autumn required a higher level of 2.2 m a.s.l. Closure of the lagoon after the 2021 opening was rapid and the lagoon has not been opened since. The coastal permit providing for openings of Waituna Lagoon expired in early 2022[1], and an application for consent renewal has been subsequently withdrawn[2].

Over the past 12 months, water level was ≥2 m a.s.l. for 70 days in winter (in July to September 2022), but only exceeded 2.2 m a.s.l. for two days. Water level in a closed lagoon is controlled by inflows, evaporation and drainage to the sea by percolation through the coastal barrier. The absence of extreme water levels fluctuations in the lagoon are likely to relate to the dryer climatic conditions experienced in Southland over the past two years according to the New Zealand Drought Index[3]. For instance, extremely dry conditions in April 2022 contributed to an extensive fire within 1370 ha of the Awarua Wetlands west of Waituna Lagoon.

Under a natural water level regime, 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. 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. The regime of artificial openings have led to longer periods when the lagoon was open to the sea.

[1] https://www.waituna.org.nz/about-waituna-lagoon/resources/lagoon-managment
[2] https://www.es.govt.nz/environment/consents/notified-consents/2022/lake-waituna-control-association
[3] New Zealand Drought Index.

2. Temporal Physico-chemical Conditions

Methods

Water quality monitoring data for Waituna Lagoon was obtained from Environment Southland from 2009 to 2023. 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 2023:

1. Chlorophyll-*a* (Chl-*a*, mg l^{-1}).
2. Salinity (Practical Salinity Unit, 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

Salinity levels in Waituna Lagoon are generally related to the opening regime. Salinity showed a steady drop over the nine months prior to the 2023 vegetation monitoring (late January), to a value of 0.9 PSU in early January (Figure 3a). Similar salinity declines are seen for extended closed periods, while after opening events salinity could approach the value of seawater (Figure 3a).

Water temperature increased by almost 15°C between August 2022 and early January 2023, to a value of 19.2°C prior to vegetation monitoring. Water temperature maxima prior to the 2023 monitoring were similar to 2018 to 2022 (>15°C), but warmer than temperature between 2016 to 2017 and 2013 to 2014, according to the Environment Southland data (Figure 3a).

In the 12 months before the vegetation monitoring in late January 2023, Chl-*a* concentration was low (<0.01 mg l^{-1}) without some of the higher peaks (>0.2 mg l^{-1}) seen in 2009, 2012, 2015 and 2018 to 2021. Although TN levels over the last year showed similar patterns to previous years with winter peaks, TP concentrations were constrained to a lower range of <0.05 g m^{-3} (Figure 3b). Both TSS and turbidity measurements in the lagoon had dropped in the 12 months before the 2023 vegetation monitoring to levels of c. 2 g m^{-3} TSS and 2.5 NTU (Figure 3c). This reduction is possibly related to increased sediment trapping capacity of *Ruppia* plants with the development of vegetation (Section 5).

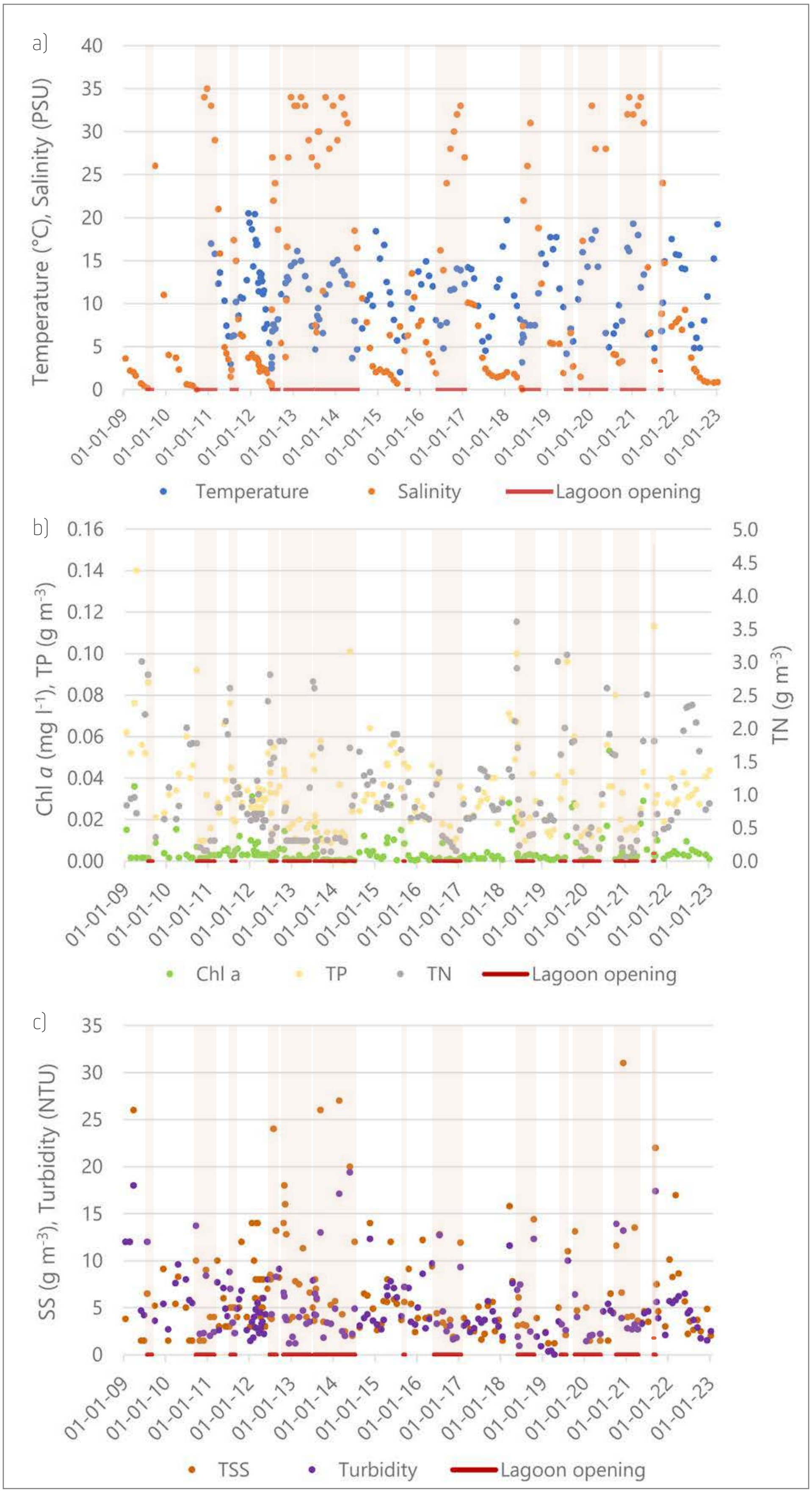


Figure 3: a) Timeseries of temperature and salinity, b) Chlorophyll-*a* (Chl-*a*), total phosphorus (TP), and total nitrogen (TN), and c) Total suspended solids (TSS) and turbidity at the lagoon centre sampled over 2009 to 2023.

Discussion

A closed lagoon over much of the *Ruppia* growing season was previously associated with lowered salinity and total suspended solids, but increased temperature and nutrients compared to an open lagoon status (de Winton and Mouton 2018a). In 2023, these associations generally held, apart from lower levels of TP (Figure 3b). It may be that reduced inputs of phosphorus resulted from reduced surface water inputs under catchment drought conditions over 2022 to 2023. A well developed vegetation in 2023 could also have reduced TP via enhanced sedimentation of suspended solids, and plant uptake.

Lagoon mouth status and the timing of lagoon openings proved major drivers of chemical conditions in the lagoon, but seasonal signals were also strong for temperature, nutrients and suspended solid concentrations (Schallenberg and Tyrell 2006, Schallenberg et al. 2010, Hodson 2017, de Winton and Mouton 2018a). In turn, these physico-chemical conditions will influence the spatio-temporal development of aquatic 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 2023 and compare with previous annual monitoring over a range of mouth status.

3. Annual Physico-chemical Monitoring

Methods

The location of 47 monitoring sites are shown in Figure 4.

At each monitoring site, measurements were made from 2009 to 2023 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, 2021 and 2022, where sites were dry we took water quality measurements close by if possible. The data is 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

In 2023, all sites were monitored for water quality, although bottom water readings for some parameters could not be measured at seven sites due to restricted water depth. The low salinity (average <1 PSU) in the most recent monitoring was similar to previous closed lagoon years (<5 PSU) apart from those with recent closure in 2016, 2017, 2019 and the drought year of 2022 (Figure 5). Much higher salinity (average >15 PSU) was observed when the lagoon was open to the sea in 2011, 2014, 2020 and 2021, but an open lagoon in 2013 was associated with low salinity.

The average water depth in 2023 was 0.76 m but ranged from 0.2 to 1.9 m at sites (Figure 5). Average water level in 2023 was higher than the monitoring occasions when the lagoon was open in 2011, 2013, 2014, 2020 and 2021, but was also higher than monitoring events in the drought years of 2018 and 2022 when the lagoon was closed at the time of monitoring. The average water temperature of 17.8°C in 2023 was similar to the 16°C to 18°C average for the majority of monitoring years (Figure 5). Most sampled sites were between 16.4 and 18.5°C, with outliers recorded along the shallow northern shore (Figure 4).

An average dissolved oxygen (DO) concentration of 10.6 mg l^{-1} in 2023 was the second highest of all monitoring years (Figure 6). Dissolved oxygen levels were supersaturated at 83% of sites, likely due to very high *Ruppia* covers (Section 5) and only two sites recorded slightly less than 80% DO. The lowest recorded DO value was 7.6 mg l^{-1} (Figure 6).

Average turbidity (NTU) was low in 2023 at a value of 3.9 (Figure 6). The highest turbidity measurements of c. 15 NTU were recorded in shallow water at two sites along the northern shoreline (Figure 4), possibly resulting from resuspension of bottom sediments by wind driven wave action.

Dense vegetation obscured black disc measurements at two sites in 2023. Elsewhere, the average black disk reading was 1.18 m (Figure 6). This value is similar to the monitoring years of 2015 to 2017, but lower than 2019 and higher than other years (Figure 6).

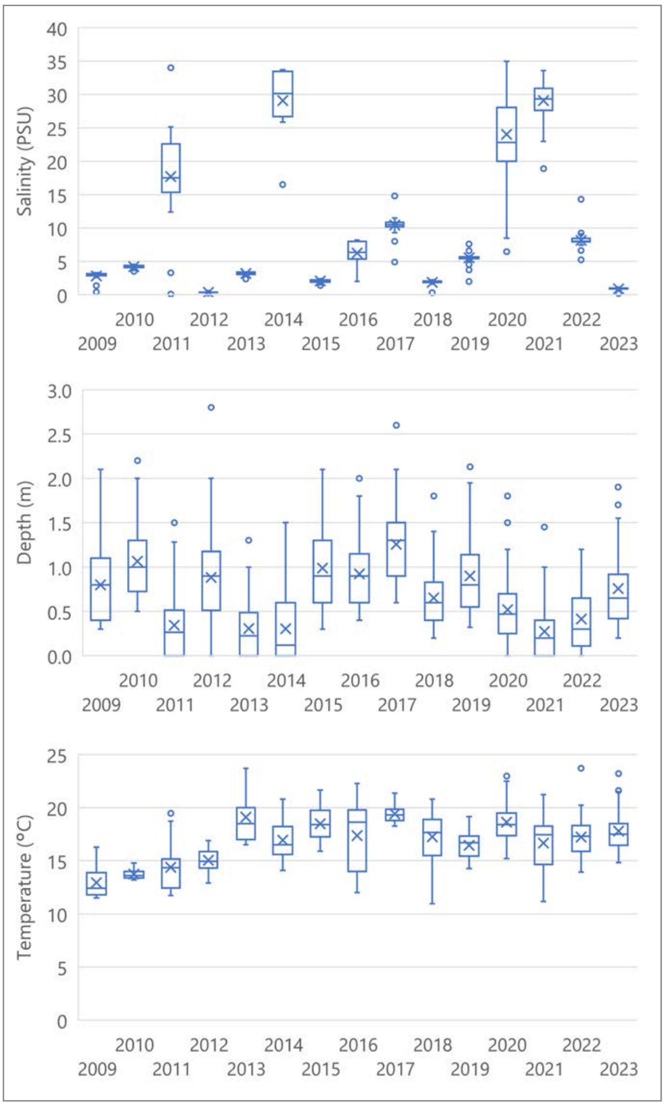


Figure 5: Box and whisker plots of salinity (top), depth (middle) and temperature (bottom) over all monitoring years. (n = 47).

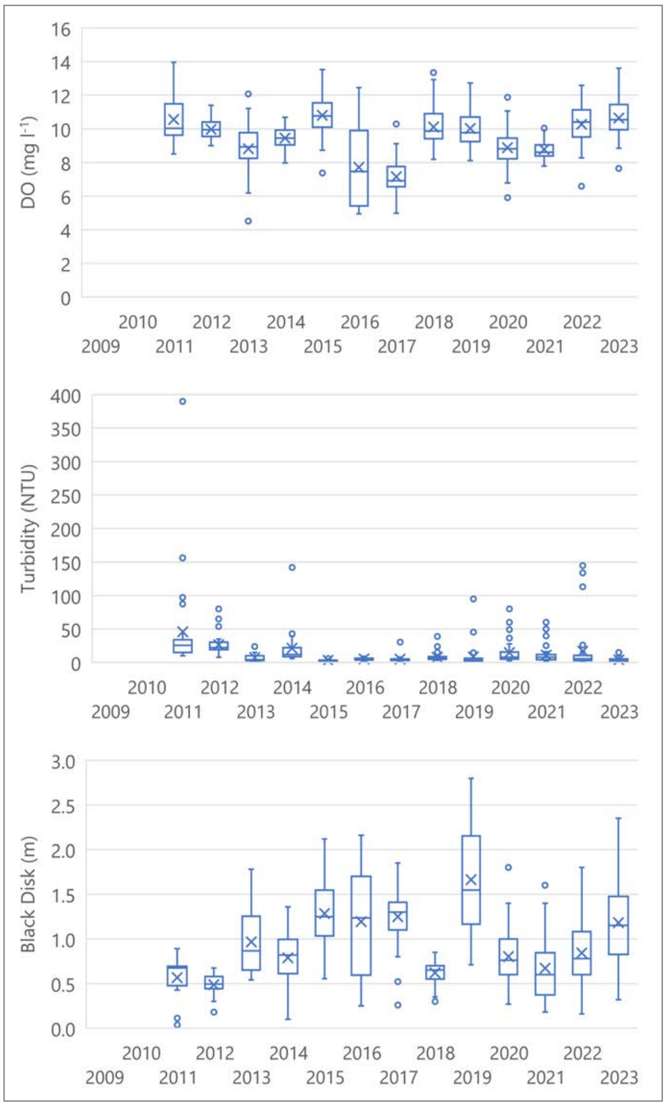
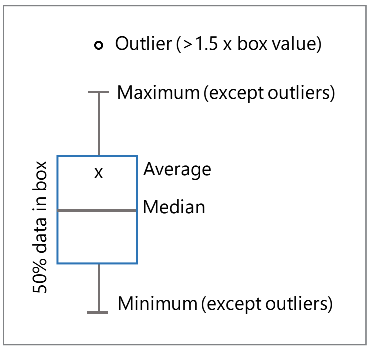


Figure 6: Box and whisker plots of DO (top), turbidity (middle) and black disk (bottom) at the monitoring sites (n = 47), from 2011 to 2023.



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

Discussion

Physico-chemical measurements at the time of the 2023 annual monitoring appeared relatively typical for closed lagoon sampling, with low salinity, and moderate water depths. Supersaturated DO conditions are likely to reflect photosynthetic gas releases associated with the high *Ruppia* biomass recorded at many sites (Section 5). DO levels were generally well above levels considered necessary for healthy aquatic life.

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

In 2023, the hoe substrates tended to be finer or softer (higher proportion of categories 1 to 3) than the previous year. The current monitoring year resembled the composition recorded in the monitoring years 2009–2011, 2015 and 2019, with a high proportion of soft mud/sand recorded (Figure 7). It also appeared that sand substrates had become muddier in 2023 than the previous year (Figure 7), potentially due to *Ruppia* capacity to trap suspended sediment and the increased vegetation development recently (Section 5).

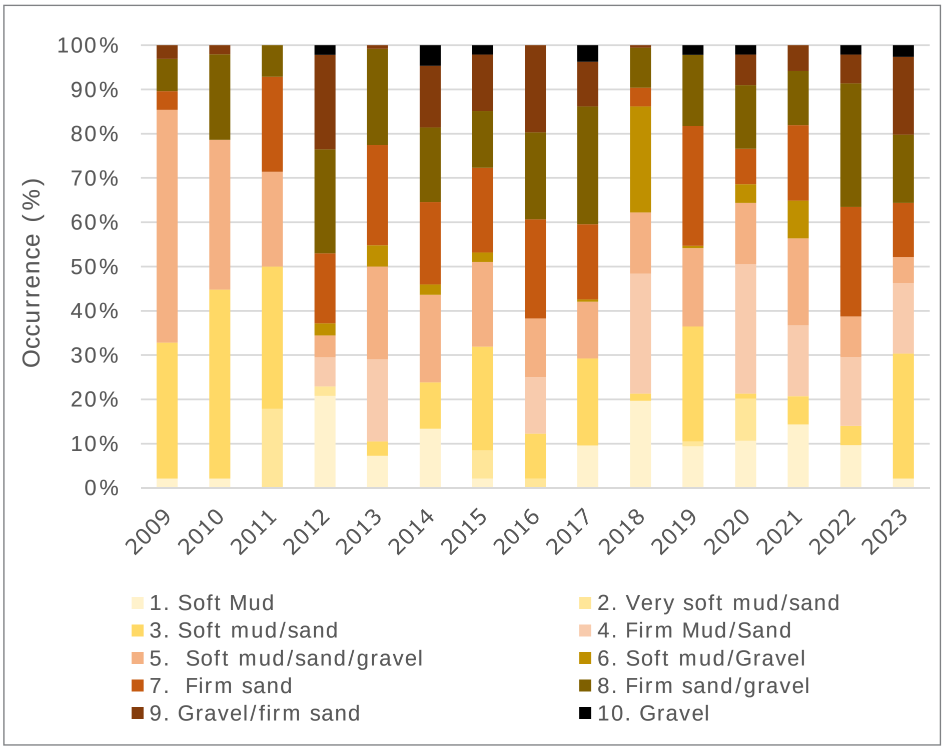


Figure 7: Bar plot illustrating the composition in substrate type (% occurrence), recorded during each of the annual monitoring surveys. Substrate types are numbered from softer to harder.

A blackened layer at the sediment surface (<1 cm depth) was recorded at only 2.7% of sampled substrates in 2023 (Figure 8), all of which comprised fine sediment of sand to mud. This was the lowest proportion for this category recorded in the last five years of monitoring. Much higher proportions of blackened surface layers were recorded in 2009, 2010, 2015 and 2019 to 2022. However, greater than 50% of substrate samples in 2023 recorded a blackened layer within the top 6 cm of sediment, a proportion greater than the previous three monitoring years (Figure 8), which likely reflects a return to greater proportions of fine substrate.

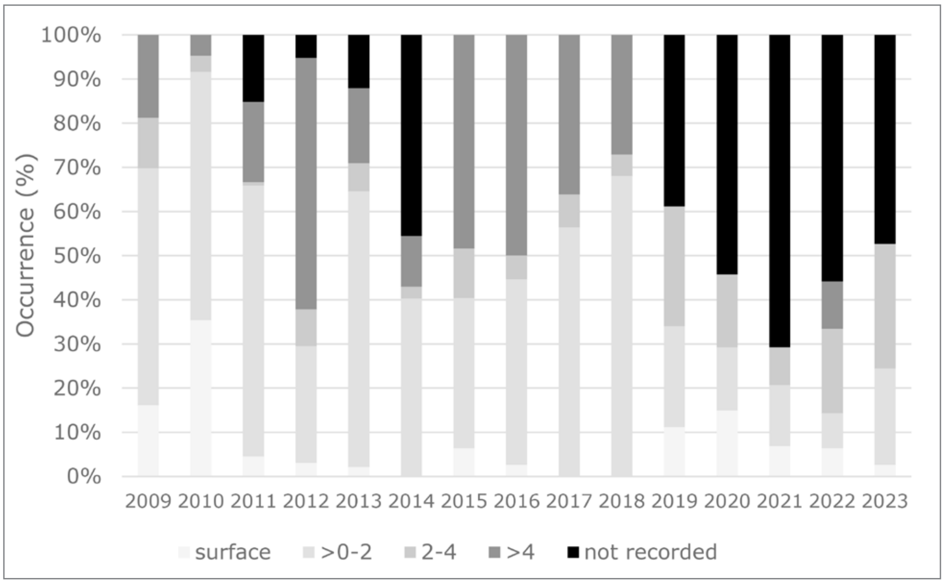


Figure 8: Substrate depth to a blackened layer shown as occurrence (% records) for five incremental depth categories.

Discussion

A redox potential discontinuity layer indicated by a blackened layer in the substrate (Stevens and Robertson 2007) suggests a reducing environment which increases oxygen consumption and, therefore, anoxic conditions as well as accumulation of phytotoxic sulphide and possible nutrient release. Therefore, increasing presence of blackened layers indicate reduced ecological health of the lagoon.

More oxidised sediments have been associated with harder substrates and indicate a better ecological condition (Stevens and Robertson 2007). Sediments had become finer and softer in 2023, possibly in association with a high biomass of vegetation under a closed lagoon which would encourage sedimentation of fines. However, substrate conditions remained similar to the previous five years, being generally oxygenated and 'healthy'. This result within generally finer substrates may reflect plant oxygen release to sediments via their roots, a recognised phenomenon of vascular aquatic plants (Thursby 1984, Kemp and Murray 1986).

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. Where covers were previously recorded as a cover score range[4] 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 range[5] 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 type present.

Results

Vegetation composition

All sites surveyed in 2023 recorded vegetation (Figure 9). *Ruppia polycarpa* was the most widespread aquatic plant recorded, being present at 45 sites. *Ruppia megacarpa* was recorded from 18 sites and extended beyond its previous typical distribution in the eastern lagoon to sites on the northern half of transect 9 (Figure 4). *Ruppia megacarpa* occurred with *R. polycarpa* at all but two of these sites. *Ruppia* species occurrence in 2023 was similar to previous high occurrence records over 2018 and 2019 of 42-45 sites for *R. polycarpa* and 14-15 sites for *R. megacarpa* (Figure 9).

Other submerged plants to increase substantially in occurrence in 2023 were the charophyte *Lamprothamnium* species[6] (23 sites) and freshwater milfoil *Myriophyllum triphyllum* (15 sites). Both species have been more conspicuous in the years that the lagoon has been closed. *Lamprothamnium* species had high frequency in 2012, 2015-2016, 2018-19 and 2022 (Figure 9). This charophytes occurrence in 2023 was the second highest after 2019 (27 sites) another year with consecutive lagoon closures during the main spring/summer growth season for macrophytes (Figure 9). *Myriophyllum triphyllum* was also frequently observed during 2018 and 2019 (15 to 20 sites), similar to 2023.

Lakeshore turf plants *Samolus repens* and *Lilaeopsis novae-zelandiae* were recorded at an increased occurrence in 2023 (Figure 9), possibly due to three previous years of low water level during summer (2020–2022) favouring these amphibious species.

By contrast to the higher plants, macroalgae were only seen at limited sites in the lagoon in 2023 (Figure 9). *Ulva intestinalis* was recorded at 10 sites, mostly in the central and western side of the lagoon. Occurrence of filamentous green algae was seen at just eight sites. Filamentous green algae were dominated by *Cladophora* species, but all algal samples collected had high numbers of sedimented diatoms (e.g., *Navicula* species). This reduction in macroalgae occurrence in 2023 contrasts with their frequency at sites over 2009 to 2022, and previously over 2015 to 2017 (Figure 9). Although hoe samples are known to incompletely sample macroalgae, wider in situ observations by divers (section 'Macroalgal cover') confirmed the limited nature of macroalgae in 2023.

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

[5] <5 cm, 5–15 cm, 15–30 cm, 30–50 cm, 50–80 cm, 80–100 cm.

[6] *Lamprothamnium* species taxonomy in New Zealand is currently unclear, but likely to include *L. compactum* (M. Casanova *pers* comm. 23/05/2023).

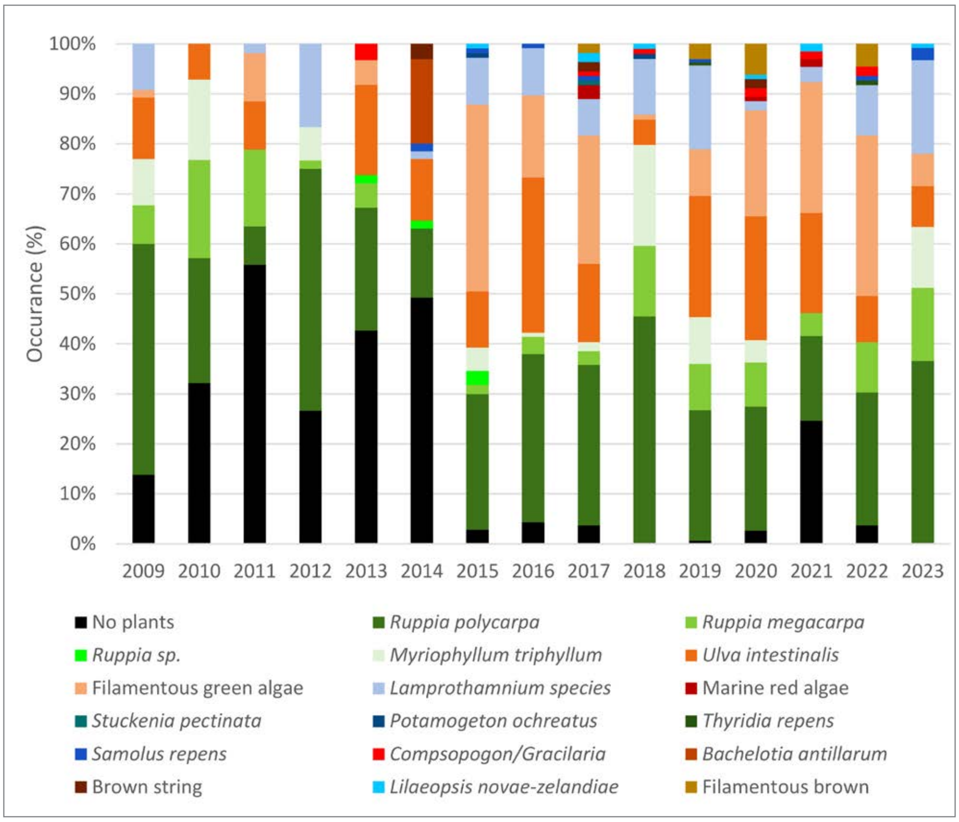


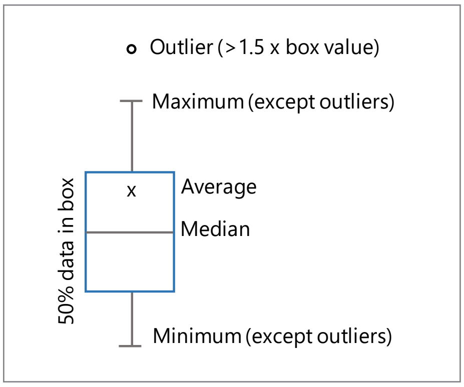
Figure 9: Vegetation composition shown as relative frequency of occurrence (sites recorded) for species or vegetation groups.

Ruppia abundance

In 2023, *Ruppia* species had the highest yet recorded average cover out of the 15 monitoring years (Figure 10a). Average cover of *Ruppia* species from hoe samples was 52% lagoon-wide (Figure 10a), compared to the next highest average of 40% recorded in 2016 and 35.6% in 2019. Both of the *Ruppia* species exhibited similar average cover for the hoe samples in 2023.

The average height of *Ruppia* plants from hoe samples in 2023, at 0.61 m, was also greater than the <0.5 m values of all previous years (Figure 10b). Together, the heights and high covers recorded contributed to a record average biomass index of 4339 (Figure 10c). The next highest average biomass index values (1000 to 2000) occurred over 2015–2016 and 2018–2019 (Figure 10c), which also represented consecutive years of a closed lagoon in the three or more months before monitoring.

High outliers in Figure 10b and 10c represent sites were dominated by *R. megacarpa*. *Ruppia megacarpa* has been disproportionately represented amongst the taller height records and higher biomass index values in all monitoring events to date.



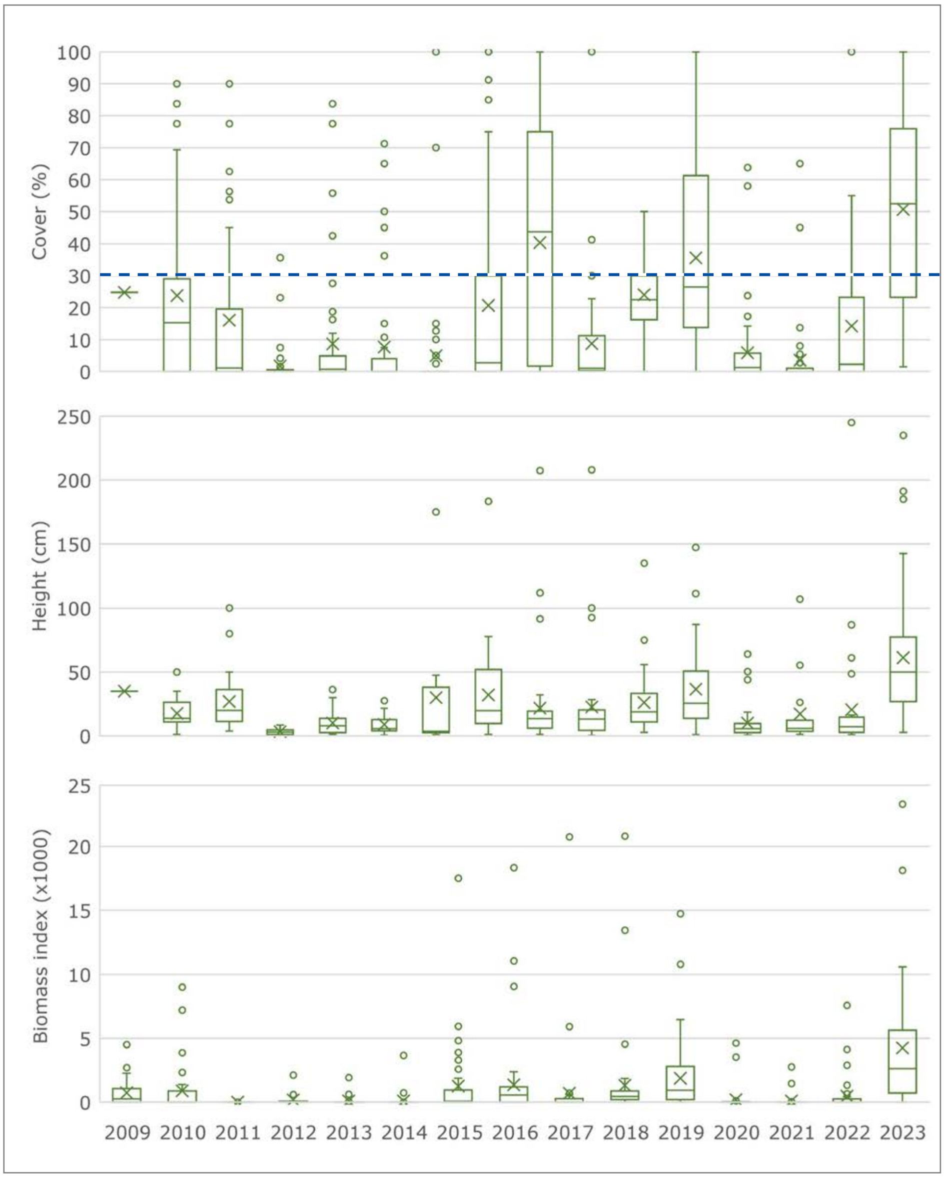


Figure 10: Box and whisker plots of *Ruppia* cover a), height b) and derived biomass index c) over monitoring years, as an average of measurements at monitoring sites (n = 47). Dotted line represents the lagoon-wide target for *Ruppia* cover of 30% identified by the Lagoon Technical Group (2013).

In 2023, *Ruppia* was observed by divers within a 10 m diameter survey area at all sites. In previous years when *Ruppia* occurrence has been much less than 100% of sites, the diver observations were more likely to detect *Ruppia* than the hoe sampling method. Diver observations of *Ruppia* covers and heights show a correlation with the hoe method (Figure 11). Average *Ruppia* cover for each method per monitoring year showed a closer correlation (R^2 = 0.94, data not shown), although the diver observations gave higher estimates than hoe measurements for 10 out of 11 years.

Diver observations of *Ruppia* in 2023 averaged 63% cover (data not shown). Again, this value was higher than previous highest average cover values observed by divers of 37% in 2016 and 50% in 2019. Diver estimates of plant height at 0.83 m in 2023 were second highest to 2019 (0.95 m). The diver method has the tendency to report taller plants than the hoe method, probably because of the larger assessed area.

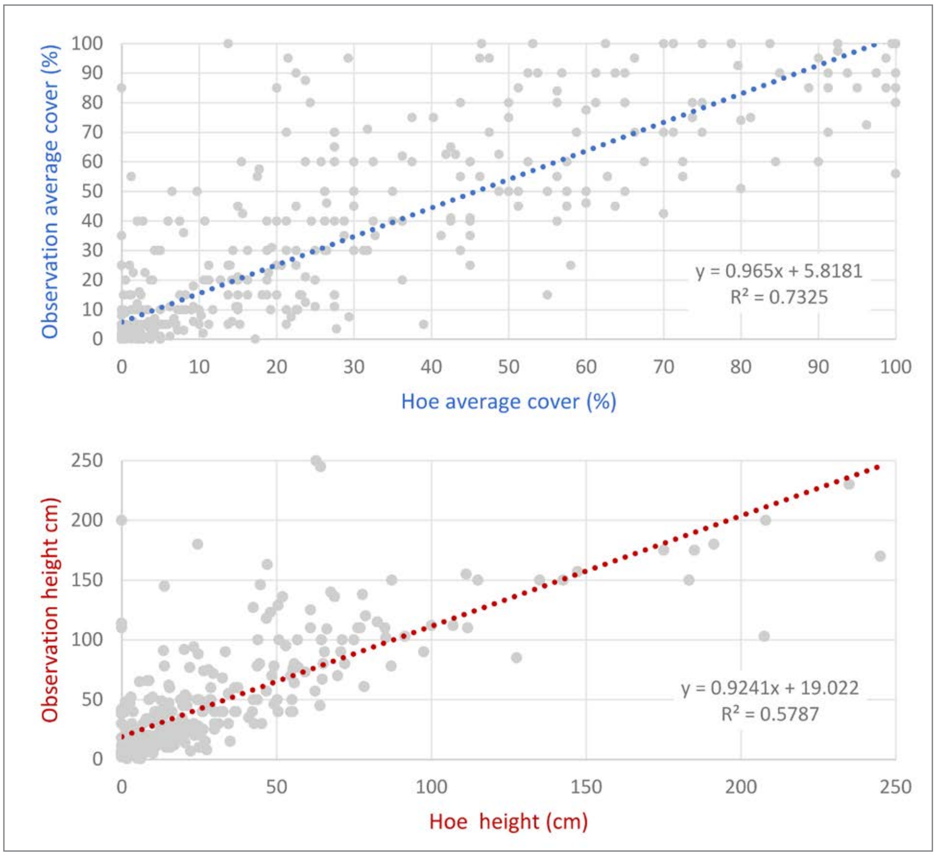


Figure 11: Relationship between *Ruppia* cover (top) and height (bottom) estimated from hoe samples and diver observations within a 10 m diameter area at each site.

Ruppia life-stage

In 2023, 85% of hoe samples (96% of sites) recorded reproductive *Ruppia* plants with flowers or developing seeds (Figure 12, Table 1). This value is higher than all the previous measures of *Ruppia* reproductive success for monitoring years. Years when the lagoon has been closed for the three months over the main *Ruppia* spring-summer growth period recorded greater than 15% hoe samples as reproductive (Figure 12, Table 1). However, a higher reproductive success was associated with the second consecutive year of closed lagoon status, for example in 2016, 2019 and 2023 (Table 1). By contrast, years with ≤10% of hoe samples recorded as reproductive were years when the lagoon was not closed for three months or more over the main growing season for *Ruppia* (2011, 2013–2014, 2017, 2020–2021, Figure 1, Table 1).

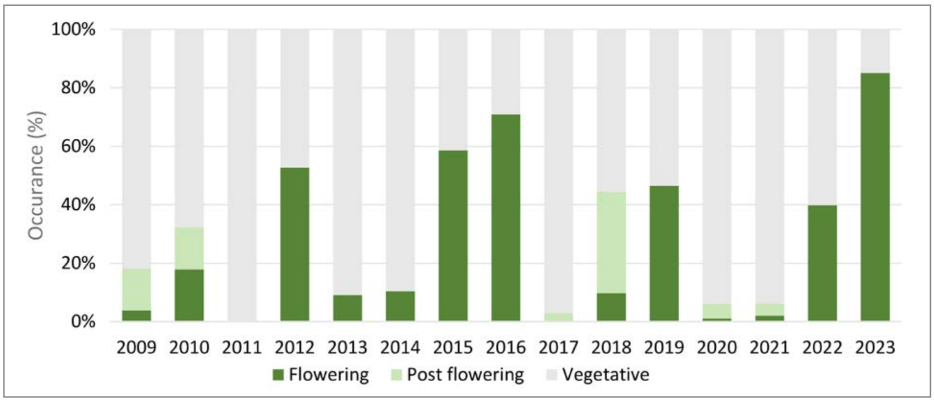
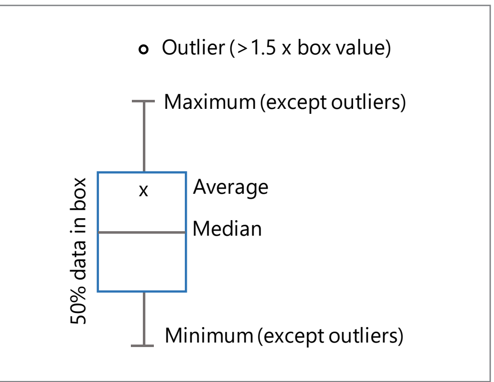


Figure 12: Life-stage category of *Ruppia* species across monitoring years as a proportion of records.

Table 1: Record of lagoon closure (months before monitoring) and reproductive success (% of hoe samples recorded as reproductive) for each monitoring year. Open lagoon shows negative value and years closed for three or more months are shaded.

Year	Months closed before monitoring	Reproduction (% samples)
2009	**4.7**	**18**
2010	**4.6**	**32**
2011	-5.6	0
2012	**4.6**	**53**
2013	-3.9	9
2014	-6.2	10
2015	**6.2**	**59**
2016	**3.2**	**71**
2017	1.0	3
2018	**13.7**	**44**
2019	**3.5**	**46**
2020	-4.1	6
2021	-4.8	6
2022	**4.5**	**40**
2023	**16.6**	**85**



Macroalgal cover

In 2023, the average macroalgae cover recorded from all hoe samples in the lagoon was low, at 5% (Figure 13). This value was low because macroalgae were only recorded at 32% of the hoe survey sites. Similar low average covers (<10%) for macroalgae cover have been recorded in 2009–2012, 2014 and 2018 (Figure 13).

Macroalgae formed covers of 100% at only one site in 2023 (Site 9.7, Figure 4). Previously in 2016, 2017, 2019 and 2022, macroalgae covers at individual sites have exceeded 100% where different macroalgae types formed overlying layers (e.g., benthic mats and surface mats).

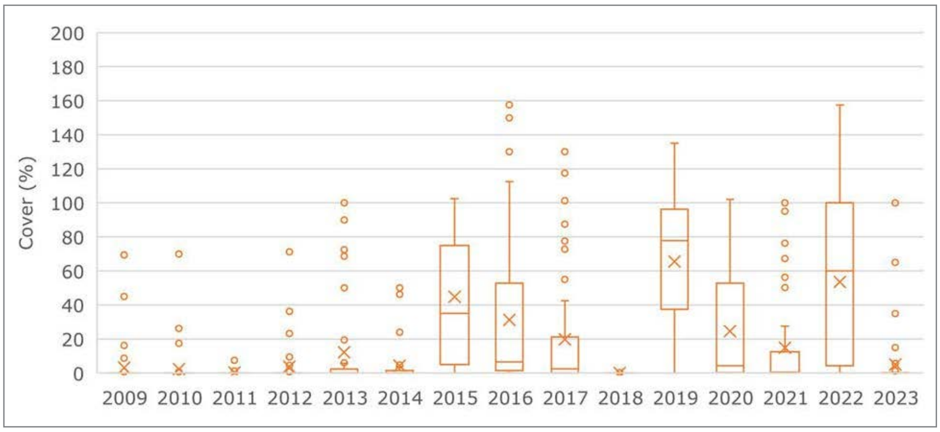


Figure 13: Box and whisker plots of macroalgae cover over monitoring years as an average of hoe measurements at monitoring sites (n = 47).

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

Dislodgment of algal cover has been observed when hoe samples were retrieved to the surface (e.g., Robertson and Stevens 2009, Stevens and Robertson 2010) and algal biomass has also been noted suspended in the water column by waves and currents and so not captured by the hoes. Therefore, an underestimation of macroalgal development is likely from hoe samples. However, diver observations over a 10 m diameter area at sampled sites in 2023 confirmed a low lagoon-wide average cover for macroalgae, with estimates of just 5.3%. The two measurements had a linear correlation ($R^2 = 0.89$) in 2023 (data not shown) that continued the relationship seen across all monitoring years (Figure 14). Average macroalgae cover for each method per monitoring year showed a closer correlation ($R^2 = 0.81$, data not shown), although the diver observations gave higher estimates than hoe measurements for 10 out of 11 years.

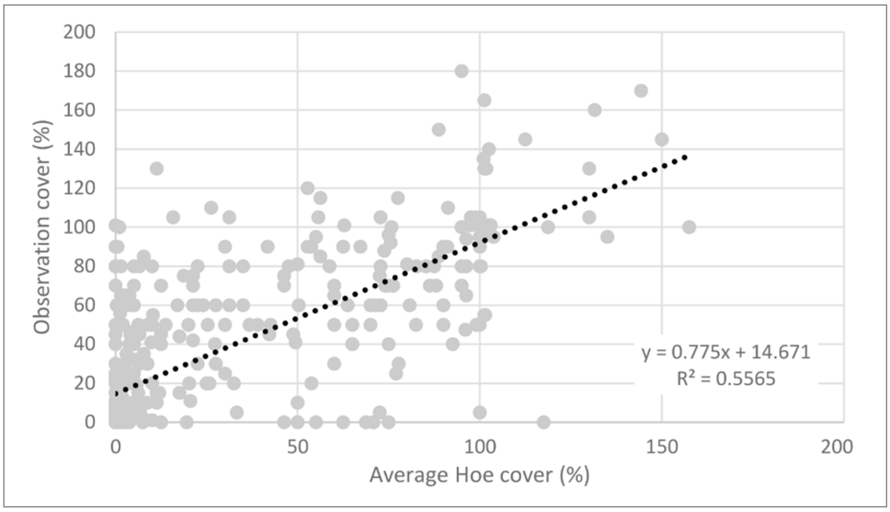


Figure 14: Relationship between macroalgal percentage cover estimated from hoe samples and diver observations within a 10 m diameter area at each site.

Discussion

The 2023 monitoring year saw records set for *Ruppia* cover, biomass index and reproductive success, with the highest average values out of the 15-year data set for annual vegetation monitoring. This 2023 year, like previous years of high *Ruppia* development in 2016 and 2019, represents the second of two consecutive years of closed lagoon over the critical growth period for *Ruppia*. Moreover, prior to the 2023 monitoring the lagoon had not experienced the disruption of a lagoon opening for 16.6 months. Dry to drought conditions recorded in Southland in 2022 avoided periods of sudden water level increase in the lagoon and possibly reduced catchment derived effects (e.g., sediment and nutrient loads). Climatic conditions also resulted in slowly falling water levels from September 2022 up until the January 2023 monitoring that would have increased light availability for plants.

Closed lagoon conditions are likely to provide conditions of sufficient water to inundate all survey sites with low, stable salinity suitable for growth. Open lagoon conditions that are detrimental to *Ruppia* development are likely to include the high and fluctuating salinity levels and tidal currents that could disturb vegetation and cause biomass loss.

The benefit of two consecutive years of closed lagoon over the critical growth period for *Ruppia* appears to provide time for vegetation colonisation to extend across the lagoon. Previously, patterns of *Ruppia* recovery in a suitable year have mainly involved the eastern sector of the lagoon, with a longer lag time apparent for the central and western lagoon. *Ruppia megacarpa* recolonisation has also lagged behind *R. polycarpa* in terms of occurrence. This longer recovery time for *R. megacarpa* means that the higher covers and biomass index associated with this species may not develop over just one year of favourable growth conditions and may require two or more consecutive years of closed lagoon conditions during the main macrophyte growth season.

In contrast to the 2023 monitoring year, an open lagoon for part of the spring to early summer growth season for *Ruppia* has previously resulted in lower vegetation development and reproductive success. *Ruppia* presence and development have been observed to decline further after two consecutive years of open lagoon status during the main growth season, for instance the 2013 to 2014 and 2020 to 2021 periods.

A major reproduction event was documented for *Ruppia* in 2023, with almost all sites (96%) recording reproductive plants. Diver's comments also indicated a large number of seeds were being produced for both of the *Ruppia* species. Addition of seed loads will replenish the seed bank, which has previously been identified as a major mechanism for vegetation recovery after long lagoon openings (de Winton and Mouton 2018b). By contrast, recovery of a related *Ruppia* species was slowed by inadequate recharging of seed banks after poor flowering success (Sinclair et al. 2020) and loss of the propagule bank was seen as a major factor restricting colonisation for an Australian *Ruppia* species (Frahn et al. 2012). Successful flowering of *Ruppia* in Waituna Lagoon is likely linked to plant biomass development (e.g., Santamaría et al. 1995). For instance, *Ruppia* plants must have sufficient energy reserves for flowering stems to reach the water surface for pollination.

Submerged plant diversity was high in the lagoon during the current years monitoring, with the highest representation by *Ruppia megacarpa* yet recorded, and second highest occurrence for the charophyte *Lamprothamnium* species and milfoil *Myriophyllum triphyllum*. Diversity was partially contributed by the appearance of freshwater macrophytes such as *Potamogeton ochreatus*.

Macroalgal development in 2023 was low in Waituna Lagoon. This result was surprising given that long closures have previously been associated with nutrient accumulation that potentially fuel macroalgal growth. It may be that reductions in surface water inflows under recent dry conditions in Southland (high drought index for 2022 and 2023[7]) have created limited nutrient availability for macroalgae in 2023. The dry year of 2018 also saw low development of macroalgae under a closed lagoon status at the time of monitoring. Although competition between abundant *Ruppia* beds and macroalgae for light and dissolved nutrients may have contributed to low macroalgae in 2023, this is not supported by results in 2019, when a high abundance of *Ruppia* was associated with the highest average cover of macroalgae recorded from 15 years of annual monitoring at Waituna Lagoon.

Also noted is that macroalgal abundance has generally been higher post-2015, despite including years of closed and open lagoon status at the time of monitoring. Overall, it appears macroalgae development is less influenced by lagoon mouth status than *Ruppia*. Macroalgae appear to respond more quickly to short-term meteorological events and their influence on catchment nutrient loading and temperature conditions in the lagoon. For instance, very rapid development of algal mats at the water surface can occur under warm, still conditions. It may also be that the amount of macroalgae that develops in one year serves as inoculum to promote levels of algal development in a subsequent year.

[7] https://niwa.co.nz/climate/information-and-resources/drought-monitor.

Informing Future Lagoon Management and Research

Ruppia is valued in Waituna Lagoon as an example of a vegetation type that is increasingly being lost in New Zealand coastal waterbodies due to water quality impacts. In Waituna Lagoon specifically, *Ruppia* is recognised as a key indicator of lagoon ecosystem health (Robertson et al. 2021) and valued as an example of intact coastal ecosystem vegetation. The current restricted distribution of *R. megacarpa* in this country means it has been designated At Risk – Nationally Uncommon under the New Zealand Threat Classification System (de Lange et al. 2018).

A 15-year long dataset of annual vegetation monitoring at Waituna Lagoon provides strong evidence that artificial lagoon openings that extend into the key spring to summer growing season for *Ruppia* are undesirable. Moreover, consecutive years when opening occurs within this timeframe additionally limits biomass development and reproduction of the plants. The key impact of an open lagoon is likely to result from high and fluctuating salinity levels that limit plant growth rates (e.g., Gerbeaux 1989), acting together with loss of plant biomass under a tidally swept and disturbed system. Sensitivity to the impacts of lagoon openings is greater for *Ruppia megacarpa*, an important 'ecosystem engineer' that disproportionately contributes to vegetation height and biomass at Waituna Lagoon.

Equally, years when the lagoon is closed during the three months leading up to summer monitoring of *Ruppia* consistently have higher plant development. Consecutive years of favourable closed conditions during this period promoted greater vegetation development and reproductive success, with the highest development occurring in 2023 when two consecutive growth periods occurred without the disruption of any opening.

Artificial openings of Waituna Lagoon had been managed since 2017 by an interim Resource Consent (20146407-01), that favoured openings outside of spring-summer growth season for *Ruppia* by setting a lower water level criteria for openings in winter. However, this consent continued to result in unpredictable timing of lagoon closure, with openings that extended into the growth season.

A review of optimal opening conditions for the ecological and cultural health of the lagoon ecosystem (Robertson et al. 2021) recommended a higher water level threshold for opening the lagoon (2.5 m a.s.l.). This change would be expected to reduce the frequency of openings. Allowance for fish passage was suggested in the form of an opening at a lower water level (1.5 m a.s.l.) during winter to spring at a maximum frequency of once every three years (i.e., opened if no openings in previous 24 months). Openings at a lower water level (1.5 m a.s.l.) to disrupt algal blooms were allowed at any time of the year if critical levels for phytoplankton measurements were reached or other risk factors such as nutrient enrichment were indicated (as determined by the Technical Advisory Group[8]).

The proposed Resource Consent conditions (Robertson et al. 2021) are likely to advantage *Ruppia* populations. They would reduce the risk of successive years of an open lagoon during key growth seasons and increase the probability of reproductive success and adequate replenishment of seed banks. It is likely that replenished and persistent seed banks will enable *Ruppia* recovery under a scenario of low frequency disruptions caused by spring to summer openings (i.e., up to every three years) to meet additional conditions for fish passage or water quality. Moreover, intermittent salinity disruptions are likely to continue to promote *Ruppia* and *Lamprothamnium* species over potential freshwater plant competitors. Proposed conditions are also likely to benefit plant species diversity at the lagoon by also suiting other plant species typical of coastal lagoons such as the milfoil *Myriophyllum triphyllum*, *Potamogeton* species and possibly *Stuckenia pectinata*, *Althenia bilocularis and Zannichellia palustris.* Reduced occurrence of low lagoon levels may also contribute to safeguarding surrounding wetlands from fire and potential impacts on water quality.

Macroalgae do not respond so clearly to management of lagoon openings as *Ruppia*. Macroalgal development has been greater at the time of the summer monitoring in recent years (within last 9 years), with the notable exception of drought years 2018 and 2023, but not drought year 2022. Macroalgal development has been broadly linked to dissolved nutrient availability, however recent trophic status trend analysis of Waituna Lagoon did not suggest nutrient levels were increasing (Robertson et al. 2021). Macroalgal growth might also be less dependent on water nutrient levels than previously assumed, with evidence for algal mat access to sediment-based nutrients (McGlathery et al. 1997). Macroalgal development may also reflect the level from a previous year. For these reasons, macroalgae would appear to be less amenable to 'disruption' from lagoon openings than phytoplankton blooms. Opening the lagoon for management of nutrient levels also has unclear benefit for limiting macroalgal development. Control of catchment nutrient loads remain vital for ensuring the dominance of *Ruppia* at Waituna Lagoon. For instance, *Ruppia megacarpa* takes up nutrients from the water via its leaves less efficiently than epiphytic algae (Dudley et al. 2001), so that large catchment inputs of waterborne nutrients are likely to advantage macroalgae development (or phytoplankton blooms) over a submerged vegetation community. Reductions in catchment nutrient loads have been recommended in the order of 50% to allow the lagoon to remain in a healthy, long-term sustainable condition (Lagoon Technical Group 2013).

[8] Environment Southland, Te Ao Marama Inc., Department of Conservation.

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