Report on Risk Assessment for Aquatic Flora of Waituna Lagoon

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EXECUTIVE SUMMARY

1. This study was undertaken to assess threats to aquatic macrophyte (see glossary) communities in Waituna Lagoon, Southland.

2. The study drew on:
   i) Samples collected and measurements made during a field trip to Waituna Lagoon,
   ii) datasets of water level, opening regime, and water quality of the lagoon,
   iii) published and unpublished reports, and
   iv) published scientific peer-reviewed literature.

3. The aquatic plant, horse's mane weed (*Ruppia megacarpa*) is a keystone species in Waituna Lagoon because of its importance as a habitat for invertebrates (see glossary) and fish, as a food source for invertebrates and waterfowl, and its role in regulating water quality. The macrophyte community of Waituna Lagoon appears to be unique in New Zealand and is similar to that which existed in Waihora/Ellesmere prior to the Wahine storm of 1968.

4. The distribution of the macrophyte community in Waituna Lagoon is delineated by a lower depth threshold caused by light limitation and an upper growth limit caused by wave wash and desiccation. Extended periods of high water are detrimental to the macrophyte community because the variable threshold of light limitation approaches the upper growth limit.

5. Maintenance of a high light environment is essential to macrophyte survival. Therefore, high water levels should persist for less than 2 months to ensure macrophyte growth is not light limited for prolonged periods of time. Phytoplankton (see glossary) biomass and suspended sediment concentrations also reduce light penetration and reduce the habitat for macrophyte growth. Phytoplankton appear to be phosphorus limited at times. Therefore, the reduction of phosphorus availability in the lagoon currently represents the best means for controlling

phytoplankton growth and biomass accumulation. Excess nitrogen is available in the lagoon, indicating the increases in phosphorous loading may result in increased phytoplankton biomass and reduced light penetration.

6. Since 1975, the opening regime has tended towards maintaining the lagoon in an open state for longer periods of time, probably resulting in higher mean salinities in the lagoon. As the optimum growth rates of *Ruppia* are between 4 and 8 ppt salinity, the opening regime may be increasingly subjecting *Ruppia* to suboptimal growth rates. Studies on *Ruppia* from Lake Ellesmere/Waihora and overseas, show that *Ruppia* seed germination and seedling establishment require periods of low salinity, and that seedling growth is reduced under low light levels associated with high turbidity. Light studies are required to see whether closing Waituna Lagoon in spring (October/November) allows sufficient light penetration to create the condition of low salinity followed by high light, which is desirable for effective seedling recruitment

7. Various threats to the maintenance of *Ruppia* beds in the lagoon may result in catastrophic macrophyte loss, with subsequent establishment of undesirable plankton (see glossary) dominance. Although our available data is inadequate to quantify risk probabilities, our current light model shows that in the event of the lagoon 'flipping' to a phytoplankton-dominated state, the present light climate and opening regime would not allow for the regrowth of *Ruppia* beds in Waituna lagoon.

8. Climate change presents new potential threats to the macrophyte community, and the ecology of the lagoon. Increasing westerly and south-westerly winds are likely to uproot macrophyte communities and increase sediment resuspension in the lagoon. Increasing precipitation is likely to result in greater nutrient and suspended sediment inflows to the lagoon. Sea level rise will likely increase the salinity in the lagoon but could benefit the aquatic macrophyte community by potentially reducing water level variation in the lagoon. On the scale of decades, changes to coastal geomorphology (such as the gravel bar barrier) will impact on the lagoon and its long-term sustainability will depend on the balance between sea level rise and increasing sediment inputs from both terrestrial and marine sources.

9. Published research on similar temperate lagoon systems with similar threats in Australia and the USA is relevant to the Waituna Lagoon ecosystem. Furthermore, the history of Waihora/Ellesmere (Canterbury) illustrates the serious consequences of ignoring the ecological

processes at work in the lagoon, and of failing to sustainably manage these important and as yet poorly understood ecosystems.

10. Recommendations for the sustainable management of the aquatic plant communities of the lagoon ecosystem are listed on page 44 of this report.

BACKGROUND TO THE AUTHORS

Marc Schallenberg obtained his PhD from McGill University (Montreal) in the area of limnology in 1993. Since that time he has worked continuously and full-time as a research fellow at NIWA and the University of Otago, specializing in, but not limited to, shallow coastal lake ecosystems. He has obtained numerous research grants from the Foundation for Research Science and Technology, The University of Otago, and other agencies. He has authored 24 scientific peer-reviewed papers and book chapters as well as numerous research reports. He has appeared as an expert witness at Environment Court and at Regional Council hearings. He has given numerous presentations at international and national scientific conferences as well as to landcare groups and other community interest groups.

Claudine Tyrrell obtained her PhD from the University of Otago in 2000 in the area of herpetology. She held a postdoc position with the University of Colorado/Unites States Geological Survey. She has worked for the Department of Conservation and specialises in the area of threatened and invasive species.

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BACKGROUND

Waituna Lagoon is a shallow coastal lagoon that lies at the centre of the Waituna Wetlands Scientific Reserve, Southland, New Zealand (Fig. 1). The outstanding biological conservation values of Waituna Lagoon and the surrounding area contributed to it being gazetted in 1971 for wetland management purposes, and later classified as a Scientific Reserve in 1983. The Waituna Wetlands Scientific Reserve was further designated in 1976 as a RAMSAR Wetland of International Importance.

Historically the lagoon had a bed of quartz gravel, fresh to slightly brackish water, and was normally closed, separated from the sea by a sand and gravel bar (referred to here as the gravel barrier bar). Kirk & Lauder (2000) defined New Zealand coastal lagoons as being of two types: river mouth lagoons and coastal lakes. Waituna Lagoon is considered the type example of the latter. Waituna-type lagoons are shallow, generally less than 3 m deep, and are normally or naturally closed to the sea, with generally low to moderate freshwater inflows and relatively low catchment sediment yields making them very sensitive to changes in catchment hydrology and sediment delivery (Kirk & Lauder 2000).

The frequency of artificial openings of the gravel barrier bar to lower the level of the lagoon, thereby facilitating drainage of adjacent farmland, has increased the proportion of time that Waituna Lagoon is open to the sea (Kirk & Lauder 2000). This has artificially lowered maximal water levels, greatly reduced the surface area and water volume, and changed the energetics of wind-driven processes such as waves, seiches (see glossary), and water currents (Kirk & Lauder 2000).

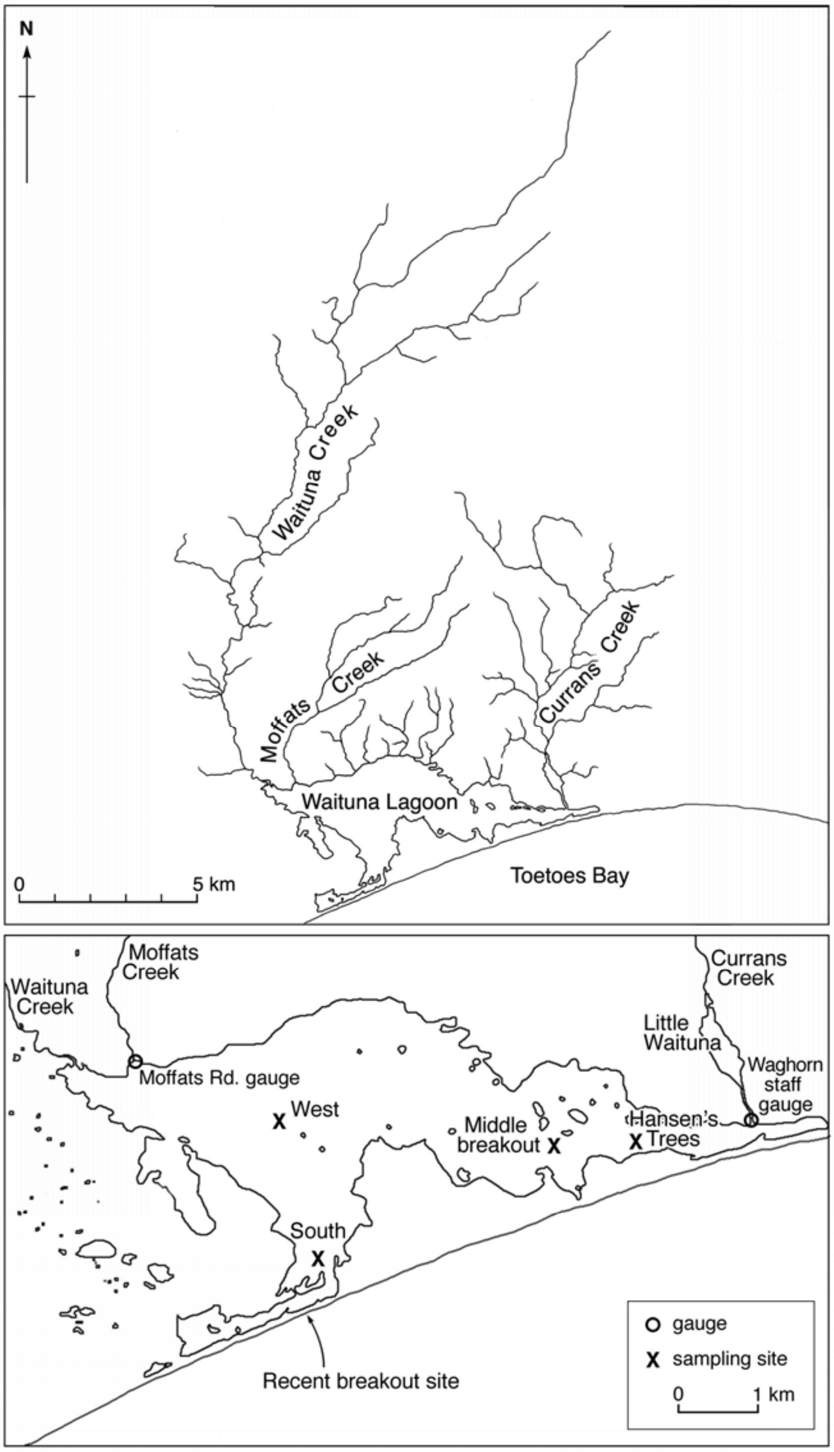

Figure 1. Location of Waituna Lagoon, Southland. Upper panel shows the extent of the catchment. Lower panel shows sampling and gauge sites.

Given the biological importance of Waituna Lagoon and the changes in catchment land use, water use, sediment loads etc., the Department of Conservation (DOC) has recommended that 'special area' status be granted the lagoon and its catchment in Environment Southland's (Southland Regional Council) Water Plan to ensure appropriate environmental management, monitoring and advocacy for the area.

The objectives of this report are to summarise the following:

1. the existing environmental information on the lagoon,
2. the environmental threats, and,
3. the likely consequences for natural values of the lagoon for issues relating to water quality and water management issues,

(with respect to the aquatic flora of Waituna Lagoon).

GENERAL METHODS

In order to assist in achieving the objectives for this study, we undertook a sampling trip on June 25, 2006, to collect macrophyte (see glossary) and light readings from Waituna Lagoon (Fig. 1b). However, the bulk of this report is based on the following sources of data and information:

1. Lagoon opening/closing regime (1967-2006; Environment Southland, DOC)
2. Water level data (1999-2006; Environment Southland)
3. Water quality data (2002-2005; Environment Southland)
4. Bathymetric data (lagoon storage; Environment Southland)
5. Meteorological data (precipitation; Environment Southland)
6. Published and unpublished reports (DOC, Environment Southland, Waituna Landcare Group)
7. Published scientific literature

ANALYSES

1. Have the frequency and duration of lagoon openings changed over time?

Prior to human influence, Waituna Lagoon would have been self-opening when water levels exceeded the lowest point on the gravel barrier. Opening would have been infrequent compared to the present regime (Kirk & Lauder 2000) and may not always have been effective in substantially reducing water levels. The opening regime has changed over time (Table 1). The first recorded artificial opening of Waituna Lagoon was in 1908, and sporadic openings prior to 1958 were organised by fishermen to improve fishing. Longer periods of closure, higher water levels and less frequent salinity fluctuations would have been the normal situation for the lagoon during this period.

Table 1. Artificial opening regime for Waituna Lagoon

Period	Opening regime	Trigger level (on Waghorn staff gauge)	Purpose	Agency
1908-57	Normally closed	High water & calm seas	Improve fishing	Local fishermen
1958-68	At least once /year	High water & calm seas	Assist drainage	Local farmers/ Dept of Lands & Survey
1969-91 1992-2006	mean = 1.6 /year (0-3 /year) mean = 0.9 /year (0-2 /year)	2 m or 1.8 m for > 2 months 2.2 m (pref. early spring to keep open as long as possible over summer)	Assist drainage	Lake Waituna Control Association / Southland Catchment Board

Following the conversion of surrounding areas into farmland in the 1950's, lagoon openings were arranged to assist drainage, though still partly funded by the Southland Acclimatisation Society, due to a continued perceived need to open the lagoon in order to improve fishing and hunting of waterfowl. The trigger water level was set according to farm drainage requirements, and water level fluctuation was reduced. Opportunities for opening the lagoon were increased.

In the Lake Waituna Control Association's 1992 application for resource consent, the accompanying EIA (prepared by the Southland Fish and Game Council) stated that "Lake opening may be required at any time during the year, but if it occurs in early spring the lake will usually stay open and maintain water levels that are conducive to grass growth and farm productivity throughout the summer". This strategy may underlie some of the changes observed in opening frequency and duration of lagoon opening since 1992 (Appendix 1).

The records of the opening regime for Waituna Lagoon (1972-2005; Appendix 1) have several gaps, and previous assessments of the duration of opening variously interpreted these gaps as lagoon open or closed (Kirk & Lauder 2000; Jackson *et al.* 2001; Thompson & Ryder 2003). In our analysis, we omitted those periods for which data are missing, and augmented the record from 20/12/1997 - 20/12/2000 with information from Jackson *et al.* (2001), and the record from August-December 2001 with information from Environment Southland.

Based on the updated information, there have been at least 51 artificial openings of the lagoon in the last 39 years (1967-June 2006; Appendix 1). The frequency of openings peaked in the early 1970's and reached a low during the 1990's (Fig. 2), when the lagoon once stayed open continuously for 864 days (Fig. 3). A regression analysis of the proportion of time that the lagoon spent open each year (between 1975-2006; Fig. 3), shows that as the frequency of openings decreased, the number of days that Waituna Lagoon spent open/year significantly increased over time ($P<0.02$). ***Since 1975, on average, the proportion of time that the lagoon has spent open to the sea has increased by 1.3% (5 days) per year.*** This is more easily seen in Fig. 4, where, except for 1993-1994, the lagoon has spent more than 12 months open out of every 2 year period since 1989.

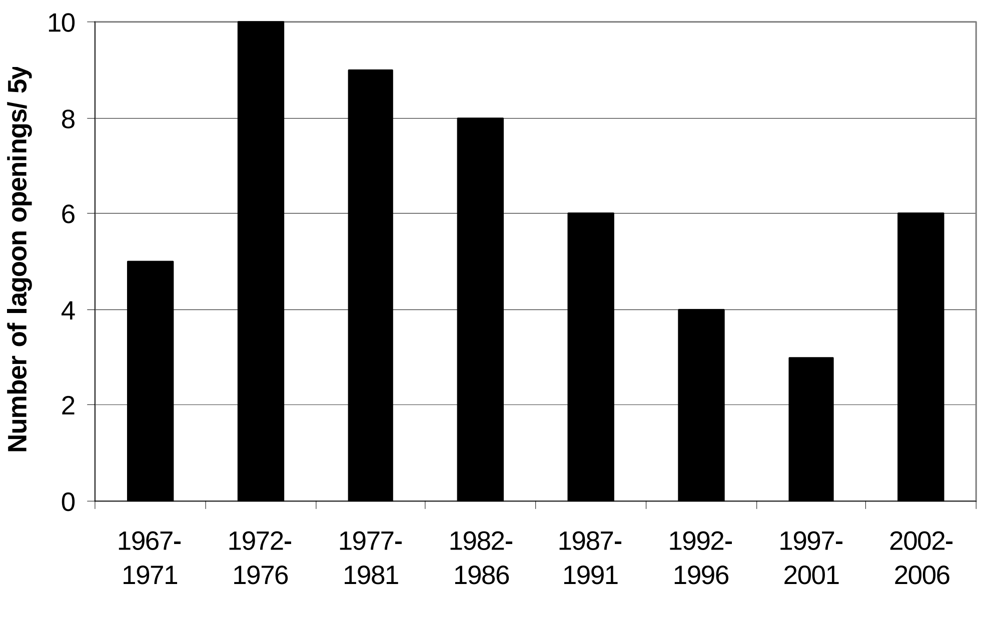

Figure 2. Number of openings of Waituna Lagoon per 5 year period, from 1967-2006.

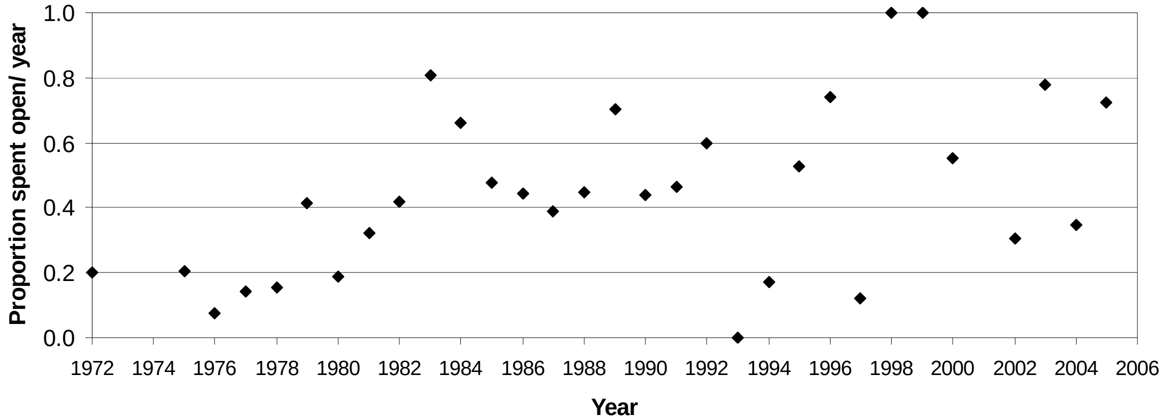

Figure 3. Proportion of time that Waituna Lagoon was open to the sea each year. Note: 2001 data unavailable.

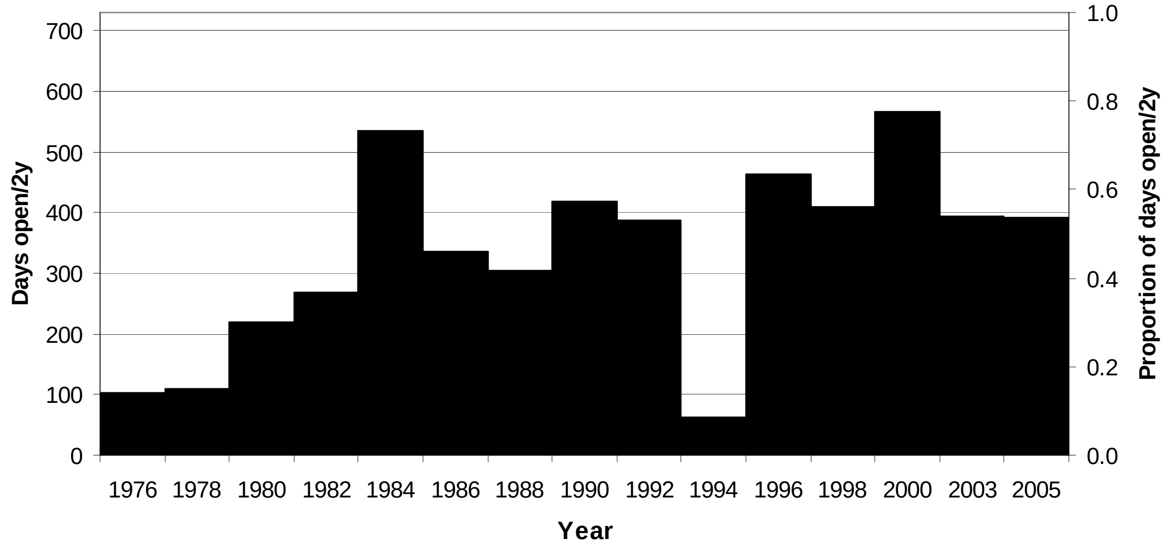

Figure 4. Days that Waituna Lagoon was open in every 2 year period (days on right-axis, proportion on left axis). Scale of x-axis shows 2nd year of pooled data. Note: 2001 data unavailable.

The length of time that the lagoon remains open depends on how long it takes for the sea to rebuild the gravel bar. However, the frequency of opening has essentially halved since 1992, when the EIA suggested that artificial opening could be timed (e.g. early spring opening) to maximize the time that the lagoon spent open.

1.1. Technical issues concerning trigger level for opening Waituna Lagoon

The present consent states that the lagoon may be opened to the sea when the water level reaches 2.2 m, as measured on the gauge board attached to the Waghorns Road Bridge (Resource Consent A0784, granted by Southland Regional Council in August 1998, for 15 years). The staff gauge is not calibrated relative to Mean Sea Level (MSL), and this has been identified as an information deficiency by previous studies (e.g. Kirk & Lauder 2000). ***Using unpublished data from Environment Southland, we calculated MSL to be 510 mm on the Waghorn staff gauge (apparent tidal range of 306.5 – 809 mm).*** This was calculated by averaging the mean daily water level measured at the staff gauge for days when the lagoon was open, and had been so for at least 7 days. In addition, we omitted water level data from days where the water level showed a sudden increase inconsistent with tidal fluctuations (e.g. due to wind-driven events or high rainfall). The data set used included water levels from 574 days.

The main environmental variable influencing the trigger level for opening the lagoon is rainfall. The area around Waituna Lagoon has a high water table, with a low hydraulic gradient, caused by subsoils with poor permeability (Jackson *et al.* 2001). Flooding occurs when the water table rises in response to high rainfall within a short time period, which, although correlated with the lagoon level, may not be the cause of flooding in areas at distances > 60 m from the lagoon or its major tributaries (Jackson *et al.* 2001). Modelling by these authors suggested that water table height in these areas was dominated by rainfall alone.

Further work is required in surveying the microtopography around Waituna, Moffats Rd, Waghorns Rd and Currans Creek, to clearly delineate the areas affected by high lake levels. The weather conditions which close the lagoon mouth appear to be those associated with flooding, and the rate at which the lagoon fills upon closing has been very similar for the past five years (Fig. 5). Based on the mean rate of filling over the past five occasions (Fig. 6), it took 16 d from the date of closure for the lagoon level to reach 1000 mm, 34 d to reach 1500 mm, and two months (59 d) after closing to reach 2000 mm.

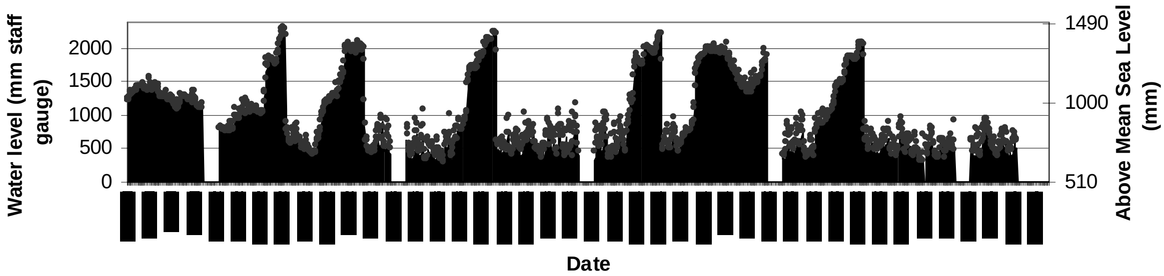

Figure 5. Daily minimum (bars) and maximum (circles) water levels in Waituna Lagoon (Environment Southland, unpublished data). Data gaps in January are due to water level not being recorded.

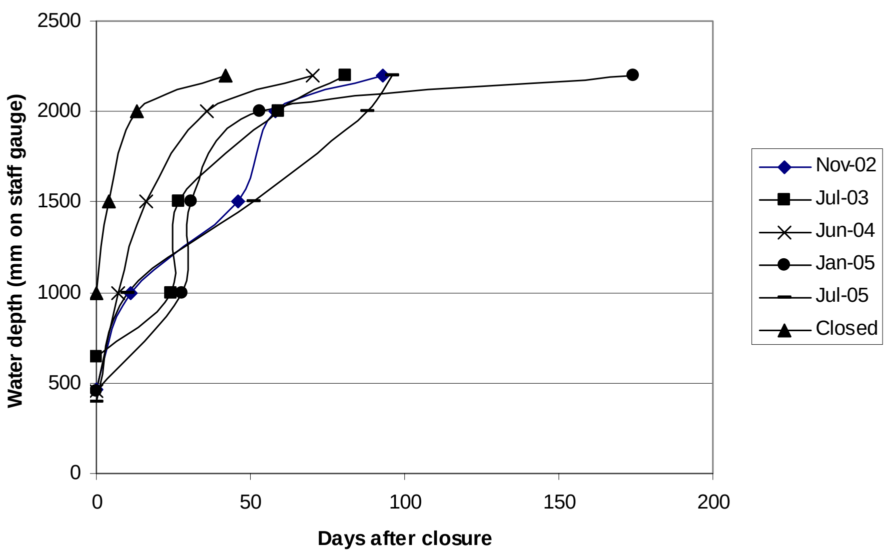

Figure 6. Water level increases in Waituna Lagoon on five occasions (dates given in legend) following closure of the lagoon outlet (raw unpublished data from Environment Southland).

The Waghorns Rd staff gauge is not located in the main body of the lagoon, and is situated up a creek at the eastern end of the lagoon. Water level measurements taken relative to this gauge at 4 h intervals by Environment Southland (unpubl. data), show that this location is subject to large seiches (see glossary) during the frequent and persistent westerly winds. According to a personal communication by Raymond Waghorn (cited by Johnson & Partridge 1998), tides cause the level to fluctuate about 300 mm when the lagoon is open to the sea, while a big wind causes fluctuations of up to 900 mm. Seiching was verified by Environment Southland data showing that during a wind event, a rise in the water level at the eastern end (Waghorns Rd) was 350 mm, with a concurrent drop in level at the western end of 300 mm (Moffats Rd). Mean lagoon level during this fluctuation was 1450 mm. When the lagoon is closed, fluctuations can be observed as a result of seiches, even during calm conditions following a wind event.

The relationship between wind and seiching is affected by water level, which determines the area and fetch of the lagoon. Seiches in Waituna Lagoon can cause localized flooding at the eastern end of the lagoon and may also cause the trigger level to be exceeded. For example, on 12 October, 2004, in the absence of rainfall, the water level rose from 1905 to 2007 mm, and then subsided to 1902 mm by the next day. This pattern was repeated on 14 October, 2004 (1902 to 2099 mm, then back down to 1902 mm within 24 h). ***Therefore, large, short-term (24 h) elevations in water level at the Waghorn staff gauge can result from wind events, and the application of the trigger level should take this into account.***

The fact that water levels have reached at least 3.45 m during stormy weather (September 1994) implies that the level required for natural breaching may be significantly higher than the current trigger level of 2.2 m. This agrees with Kirk & Lauder's (2000) assessment that Waituna-type lagoons naturally had higher maximum water levels and larger ranges of water levels than their managed levels. The nature of the vegetation on the lagoon margin has changed in response to the generally lower water levels (Johnson & Partridge 1998), and it is important to find out how aquatic macrophytes are affected by the current water level management. ***Many of the botanical values of the reserve are the result of occasional flooding of areas and the maintenance of a high water table (Department of Lands and Survey 1984).***

2. Context and value of macrophytes of the lagoon

The vegetation of the lagoon edge was examined by Kelly (1968) and Allen *et al.* (1989), but to date there has been only one detailed assessment of the submerged aquatic macrophytes of Waituna Lagoon (Johnson & Partridge 1998). ***Johnson & Partridge described the lagoon as***

unique because of its intact Ruppia-dominated macrophyte communities. When they sampled the area in 1995, freshwater plants dominated most of the lagoon, and there was a macrophyte zonation pattern with water depth (Table 2). Deeper waters (> 0.5 m depth, lagoon level at 1.25 m) were dominated by dense beds of horse's mane weed (*Ruppia megacarpa*) or water milfoil (*Myriophyllum triphyllum*), whereas shallower, silty bays had a more diverse community of low-growing plants such as *Glossostigma elatinoides*, *Lilaeopsis novae-zelandiae* and *Selliera radicans*. Aquatic algae able to tolerate salt water (e.g. *Enteromorpha* spp. and *Bachelotia antillarum*) were found only at the western end of Waituna Lagoon, near its outlet (Johnson & Partridge 1998). Several aquatic plants were notable by their absence, including charophyte algae (see glossary), *Lepilaena bilocularis*, *Zannichellia palustris*, or *Potamogeton pectinatus*. These are all to be found in brackish waters, at least as far south as Otago. ***It is likely that these plants are unable to survive the extreme salinity variations typical of Waituna Lagoon. These salinity variations may protect the lagoon from invasive aquatic plants, underscoring the need for salinity data to be collected during routine water quality monitoring of the lagoon.***

Table 2. List of aquatic plants in Waituna Lagoon (from Johnson & Partridge 1998). All are native, except for *Ranunculus*.

Plant species	Depth (m) – relative to lagoon level 1.25 m (Waghorn staff gauge)			
	0.1 - 0.4 SW end - saltier	0.1 - 0.4 most shores, exposed to wind/waves	0.5 - 0.7 relatively sheltered	1.5 - 2.0
Ruppia polycarpa	present	sparse, c. 10cm tall		
Myriophyllum triphyllum		sparse, c. 10cm tall	25% cover - sheltered sites	dense beds – mostly in sheltered bays
Glossostigma elatinoides		very scattered		
Lilaeopsis novae-zelandiae		very scattered		
Mimulus repens		very scattered		
Selliera radicans		very scattered		
Ruppia megacarpa			25% cover - sheltered sites	dense beds, mostly in main body - wind/waves
Enteromorpha sp.	present			
Bachelotia antillarum	present			
Potamogeton ochreatus			seen at one site	
Ranunculus trichophyllus		few plants East end		

When Johnson & Partridge sampled the lagoon, it was closed (3-9 April 1995, 210 d closed) and open (31 July 1995, 19 d open following 310 d of closure). At the time of sampling for the present study (25 June 2006), the lagoon had been closed for 23 d, after being open for the previous 330 d. The condition of the lagoon was therefore very different from that experienced by Johnson & Partridge (1998).

Johnson & Partridge (1998) made their observations using specimens either collected at arms length in water of wading depth, or brought up from deeper water on the end of an oar. They also checked for additional species in the aquatic debris cast up on the strand. Water depths were measured at various points around the lagoon, and ranged from 1.6 m at Waituna West to 3.2 m near the Middle Break. No aquatic macrophytes were visible on the surface of the lagoon and the water was noticeably stained with humic acids. Secchi disk depths ranged from 1.07-1.19 m. Light measurements (photosynthetically active radiation, PAR) indicated that the 1% PAR level (euphotic depth) was 1.8 m below the surface of the lagoon, with insufficient light for plant growth in the deepest parts of the lagoon. Macrophytes were sampled in four locations using an Eckman dredge, and also by removing samples caught while gently pulling the anchor in.

We found the distribution of aquatic macrophytes was very restricted (Table 3), with only one of the four sites (water depth 1.8-2.2 m) having abundant and healthy *Ruppia* sp. (stalks up to 0.5 m long). Johnson & Partridge (1988) identified both *R. megacarpa* and *R. polycarpa* from Waituna Lagoon. As there were no flowers or fruit in our samples, we were unable to identify the plants to species level, although descriptions of growth form in Johnson & Partridge (1988) suggest that we had sampled *R. megacarpa*. A filamentous red alga sp. was present at all sites, often growing as epiphytes on *Ruppia*. The brackish/marine alga, *Enteromorpha*, was present at all sites except Middle Break.

Table 3. List of aquatic macrophytes and invertebrates (see glossary) collected from four sites in Waituna Lagoon on 25 June 2006 (1.48 m water level on Waghorn staff gauge).

	Waituna West (1.6 m) (GPS ref. 2170412/5395737)	Hansen's Trees (1.8 – 2.6 m) (GPS ref. unavailable)	Middle Break (3.2 m) (GPS ref. unavailable)	Waituna South (2.2 m) (GPS ref. unavailable)
Ruppia sp.	-	abundant healthy stems up to 0.5 m long	-	present (stems 0.2 m long)
Red filamentous alga	sparse, on dead macrophyte stems	abundant, associated with *Ruppia*	sparse	abundant
Enteromorpha spp.	present	present (*E. prolifera*?)	-	present (*E. prolifera* and *E. intestinalis*)
Marine alga (branched)	dead stems	-	sparse	abundant
Invertebrates	*Potamopyrgus*, caddis cases, small cockles	Amphipods, crabs, isopods	Amphipods, caddis cases	*Potamopyrgus*, caddis case, crabs, cockle shells, mud snail

There were more plant species, and in greater abundance, observed in April 1995 by Johnson & Partridge (Table 2) than in our samples. There has also been a shift in the distribution of brackish-water tolerant species, with *Enteromorpha* spp. and other unidentified species of marine algae present in all parts of the lagoon in June 2006, rather than being confined to near the lagoon opening in the southwest (Johnson & Partridge 1988). We did not find *Myriophyllum triphyllum*, a species relatively intolerant of salinity. These two aquatic plants provide an important habitat for aquatic invertebrates (see glossary) and fish, but are also grazed by waterbirds. During the study in April 1995, with a water level of 1.25 m, Johnson & Partridge noted that *Ruppia megacarpa* had abundant flowers on the surface of the lagoon and masses of stems and foliage had to be disentangled from the outboard motor propeller. This level of growth and biomass was not seen in June 2006.

Dense beds of submerged plants act as a physical buffer to wave action, helping to prevent shore erosion (Gerbeaux 1989). Aquatic vegetation increases rates of localised sediment deposition in and around plant beds because plants trap moving sediment particles (Søndergaard & Moss 1997). As the basement substrate of the lagoon consists of compact, water-worn quartz gravel and sand (Cadmus 2004), new areas of fine sediment deposition and shelf building around macrophyte beds provide new sediment environments for flora and fauna, possibly increasing the likelihood of new macrophytes establishing within the lagoon. The establishment of new species or communities of macrophytes can be indicative of changing environmental conditions and macrophyte communities can be useful indicators of environmental conditions in lakes (Clayton *et al.* 2002). Johnson & Partridge (1998) recommended regular monitoring of aquatic habitats within Waituna Lagoon.

No rare/threatened submerged aquatic plant species have been recorded from the lagoon. However, some plants in its shore communities are listed as vulnerable (*Isolepis basilaris* and *Deschampsia caespitosa* var. *macrantha*). The shore communities are dependent upon flooding events from the lagoon to maintain the diversity of vegetation types (Department of Land and Survey 1984).

Of primary conservation value is the fact that Waituna Lagoon harbours possibly the last example of a large, intact, Ruppia-dominated macrophyte community in New Zealand, especially since the destruction of the dense Ruppia beds in Waihora/Ellesmere by the Wahine storm of 1968 (Hughes et al. 1974).

3. The role of aquatic macrophytes in the food web of Waituna Lagoon

The aquatic macrophytes of Waituna Lagoon are grazed directly by waterfowl and invertebrates, and provide habitat for invertebrates and small fish, that in turn are eaten by larger fish and piscivorous birds.

Birds:

Seventy-six species have been recorded in Waituna Wetland Scientific Reserve, including both national and international migratory waders (Rance & Cooper 1997). Appendix 2 lists birds recorded from the reserve which depend directly on the lagoon.

Different bird species use the lagoon area in different ways, and most have seasonal patterns of abundance. Twenty-seven bird species are classed as being resident at Waituna (Thompson & Ryder 2003); of these, seven are endemic and 17 are native. The three introduced resident species are game birds: black swan, Canada goose and mallard. These waterfowl, along with resident Paradise shelduck and grey duck directly graze aquatic macrophytes. Although these species may also graze on adjacent terrestrial plants (and in some cases become a pest on farmland), a crash in the population of black swans in Wainono Lagoon was brought about by a decrease in aquatic plants due to drought (Pierce 1980). Similar effects in Waihora/Ellemere were attributed to the catastrophic loss of macrophytes following the Wahine storm of 1968 (Adams 1971; O'Donnell 1985). A literature review of *Ruppia* spp. suggests that macrophytes of the *Ruppia* genus are also important in waterfowl diets in Australian lagoons (Nicol 2005).

Of concern for management of shallow lakes is that overgrazing of macrophytes by waterfowl can severely decrease macrophyte abundance and biomass in shallow lakes. Gerbeaux (1993) suggested that a swan density in Waihora/Ellesmere of 25 swans/ha in 1987 substantially restricted regrowth of macrophyte biomass in the lake. Mitchell *et al*. (1988) found that waterfowl densities were negatively correlated to macrophyte biomass in Tomahawk Lagoon (Otago).

By enhancing sedimentation, macrophyte beds improve water clarity, benefiting visual predators of aquatic fish and invertebrates such as Caspian terns and little shags (Pierce 1980). In addition, seeds and detritus (dead plants) from the commonest submerged aquatic plants (*Ruppia megacarpa* and *Myriophyllum triphyllum*) drift ashore (Johnson & Partridge 1998) providing significant food for invertebrates (e.g. amphipods), which in turn provide food for waterfowl and wading birds (e.g. marsh crake; Heather & Robertson 2000).

Suitable water level regimes are critical to the breeding and feeding habitat available to different birds. High water levels are more desirable during autumn and winter when waterfowl numbers on lakes are high. For example, nesting duration of black swans at Waihora/Ellesmere was determined by water levels; if the water level dropped rapidly (usually due to an artificial lake opening), food was available for a shorter period and breeding ceased (Williams 1980). O'Donnell (1985) noted that if Waihora/Ellesmere remained open for a long time, the water level became so low that foreshore areas dried out completely and usable habitat was restricted to a zone within 10 m of the lake shore. However, if the lake was closed for a long time, water levels might become too deep for wading birds. In Wainono Lagoon, Pierce (1980) noted that high water levels did not affect feeding in birds such as pukeko, white herons, black-billed gulls, banded dotterels and South Island pied oystercatchers, because they were able to feed in the drains entering the lake, and/or on terrestrial invertebrates such as grass grubs and earthworms. Although very low water levels exposed mudflats within the lagoon, they also caused species such as South Island pied oystercatchers to leave, as adjacent pasture got dryer, harder to probe, and prey went deeper into the soils (Pierce 1980).

Waituna Lagoon is an important southern overwintering area for New Zealand shorebirds; hosting six of the seven species of indigenous-breeding shorebirds found on the mainland (NZ pied oystercatcher, variable oystercatcher, pied stilt, Southern NZ dotterel, banded dotterel and wrybill; Dowding & Moore 2006). In addition, endemic black-billed gulls and black-fronted terns, both classified as being in serious decline, can be found over-wintering at Waituna. During the same period (Sept-April), the lagoon acts as a summer refuge and feeding area for up to 16 transequatorial migrant bird species (Department of Lands and Survey 1984). Five of these migrant waders (Pacific golden plover, turnstone, lesser knot, red-necked stint and bar-tailed godwit; Dowding & Moore 2006) are considered indigenous in the New Zealand Biodiversity Strategy (Anon. 2000). The majority of these wading birds would be negatively affected by the loss of macrophyte beds in Waituna Lagoon.

Fish:

The fish species found in Waituna Lagoon (Riddell *et al.* 1988) do not feed on macrophytes. However, aquatic macrophytes benefit fish by: i) providing food resources and habitat for invertebrate prey such as amphipods, mysids and snails; ii) providing important habitat for fish activities (e.g. feeding); iii) reducing turbidity; and, iv) providing refugia from predation by larger fish and birds.

Humphries *et al.* (1992) found that fish density in an Australian lagoon was much greater within dense *Ruppia* beds than in open water, suggesting that *Ruppia* was a favoured habitat for some species of fish species.

Of the fish species recorded from Waituna Lagoon and tributaries, *Gobiomorphus* spp., *Galaxias maculatus*, *G. argentus*, *G. fasciatus*, and juvenile brown trout might be the most advantaged by the presence of *Ruppia* refugia, whereas predatory adult trout and eels probably exploit the high fish and invertebrate densities associated with *Ruppia* beds.

Invertebrates:

Aquatic invertebrates have not been intensively studied in Waituna-type lagoons, but appear to be limited to relatively few species because salinity levels fluctuate. Macrophytes, including *Ruppia*, are important sources of food for aquatic invertebrates because: i) they can be ingested directly by some invertebrate taxa; ii) they provide an excellent substrate for the growth of diatom biofilms which are important food sources for many grazing invertebrates; and, iii) they produce organic detritus which enriches the sediment and shorelines, fuelling detritivores and detritivore-based food chains (Gerbeaux 1989; Nicol 2005).

Riddell *et al.* (1988) found that the benthic (see glossary) invertebrate fauna sampled in Waituna Lagoon in August 1985 was dominated by amphipods (*Paracorophium excavatum*), snails (*Potamopyrgus antipodarum*) and worms (platyhelminths and annelids). Species diversity was low (9 taxa from 3 sampling sites) and animals were patchily distributed. Riddell *et al.* (1988) also identified 9 planktonic invertebrate taxa from four sites in Waituna Lagoon, including two species of copepod (unidentified but likely to include the estuarine calanoid, *Gladioferens pectinatus* - abundant), amphipods (*Paracalliope fluviatilis* - present) and mysid shrimps (*Tenagomysis* sp. - common). No cladocerans were recorded, but Schallenberg *et al.* (2003) found that cladocera from another coastal lagoon did not survive in even mildly brackish waters.

Riddell *et al.* (1988) noted that few aquatic macrophytes were present in Waituna Lagoon. Our very cursory sampling of benthic invertebrates in Waituna Lagoon was also carried out in winter; however, we sampled one site in which *Ruppia* was abundant (Table 3). Amphipods and isopods (*Austridotea annectans*) were abundant in the *Ruppia* beds, as were decapod crabs. The pill-box crabs, *Halicarcinus* sp. (probably *Halicarcinus whitei*, C. McClay pers. comm.) were identified by local fishermen (C. and W. Owen) as being an unusual species for Waituna Lagoon, but are often found in estuaries in Otago, being tolerant of lower salinities and able to survive in freshwater for long periods (C. McLay, University of Canterbury, pers. comm.). Outside the macrophyte beds, snails (*Potamopyrgus antipodarum*), small marine bivalves (possibly *Austrovenus stuchburyi*), amphipods, crabs, and empty caddis fly cases were found in lower densities. Pipis (*Phaphus australe*) and other crabs (*Helice crassa* and *Macrophthalmus hirtipes*) have been also been reported from the lagoon (Ken Murray, DOC Southland, pers. comm.). Vertical density stratification of the lagoon during times of closure probably maintains salinities in the bottom waters favourable to marine species, increasing the diversity of invertebrate prey in the lagoon. However such stratification (as suggested by vertical salinity profiles on 29 September, 2003 at Waituna South and West sites; ES water quality data), if persistent, could also lead to de-oxygenation of bottom waters.

In general, the aquatic invertebrate fauna of Waituna Lagoon was similar to Waihora/Ellesmere and Wainono Lagoon (South Canterbury), where midges, mysids, crane flies and amphipods were common (Pierce, 1980).

Phytoplankton:

In shallow lakes and lagoons macrophytes may successfully compete with phytoplankton for nutrients, thereby maintaining low phytoplankton biomass, high water clarity and high light penetration (Søndergaard & Moss 1997; Dudley et al. 2001; Prof. Di Walker, UWA, unpublished data). The presence of macrophytes tends to shift the phytoplankton community to smaller, motile algae (e.g. phytoflagellates), which are considered more edible by zooplankton than large species, which tend to dominate in the absence of macrophytes (Søndergaard & Moss 1997). In addition, macrophytes can compete with phytoplankton by producing allelopathic chemicals, substances which specifically inhibit the growth of some species of phytoplankton (Søndergaard & Moss 1997). There is ample evidence in the literature that in shallow lakes and lagoons, macrophyte biomass is negatively correlated with phytoplankton biomass and there are many examples of lakes which have lost their macrophyte cover becoming subject to persistent algal blooms (Scheffer 1998). Therefore, macrophytes probably also play a pivotal role in regulating the planktonic food web of Waituna Lagoon.

4. Analysis of water quality in relation to phytoplankton biomass

Nothing is known of the phytoplankton taxa in Waituna Lagoon as no microscopic counts have been undertaken. However, phytoplankton biomass (as indicated by chlorophyll *a*) and water quality data have been regularly sampled in the lagoon since 2001 by Environment Southland. More detailed water quality data from the lagoon and its tributaries can be found in Thompson & Ryder (2003). The following analysis is based on a water quality dataset belonging to Environment Southland, collected at four sites in the lagoon on a monthly basis from October

2001 to the end of 2005. The variables that we analysed are summarised in Table 4.

The water quality of Waituna Lagoon is subject to three important drivers: i) the opening and closing of the lagoon; ii) the effects of episodic high winds causing sediment resuspension; and, iii) increasing development in the catchment, resulting in increasing loads of sediment and nutrients to the lagoon (Thompson & Ryder 2003). The first two drivers can be seen as natural influences, although the opening regime is now subject to a high degree of management. Together, they result in a highly dynamic environment creating large variation in salinity, turbidity, and nutrient levels. The opening of the lagoon allows for the exchange of fresh and salt waters, creating the potential for persistent vertical stratification of the water column due to high water density differences (e.g. Environment Southland salinity profiles, 29 September, 2003). However, the temporal and spatial extent of vertical stratification in Waituna Lagoon is unknown.

Table 4. Summary of water quality variables analysed from ~85 samples taken from four sites in Waituna Lagoon between October 2001 and December 2005.

Variable	**Units**	**Min.**	**Mean**	**Max.**
Temperature (temp)	ºC	4.9	11.1	22.0
Total nitrogen (TN)	mg l^{-1}	0.10	0.62	1.90
Total phosphorus (TP)	mg l^{-1}	0.01	0.04	0.19
Nitrate + nitrite	mg l^{-1}	0.01	0.24	1.1
Dissolved reactive phosphorus (DRP)	mg l^{-1}	0.005	0.014	0.041
Ammonium	mg l^{-1}	0.010	0.042	0.320
Turbidity	NTU	1.9	8.4	65.0
Chlorophyll *a*	mg m^{-3}	0.4	3.7	17.0

The data were carefully edited for errors. Concentrations below detection limits were given a value of one half of the detection limit. Data were log transformed to normalize variances and a principal components analysis (PCA) was undertaken to determine the major patterns of water quality. Two further datasets were used in the analysis. Continuous water level recordings at the Waghorn staff gauge were used to determine the water levels at the times of sampling, and historical records of lagoon opening and closing were used to determine the number of days that had elapsed, at the time of sampling, since the previous opening or closing date. Days since closing were given a positive value and days since opening were given a negative value. In this way, the influence of time elapsed since opening/closing could be analysed.

The results are presented in Figs. 7-10. Below are our interpretations of this preliminary analysis, primarily as it applies to phytoplankton ecology of the lagoon:

1. Axis 1 (x-axis) explained 40% of the variation in the data. Clearly the major axis of variation relates to nitrogen concentrations in the lagoon, which was driven by lagoon closure (Fig. 7). As indicated by the PCA analysis, there was a strong positive correlation between water level and TN concentration in the lagoon (Fig.8; $R^2 = 0.71$, $P < 0.0001$). High levels of nitrate in Waituna Ck. (Thompson & Ryder 2003) are consistent with this pattern observed in Waituna Lagoon, although newly flooded soils/sediments may also contribute nitrogen to the lagoon as water levels rise.

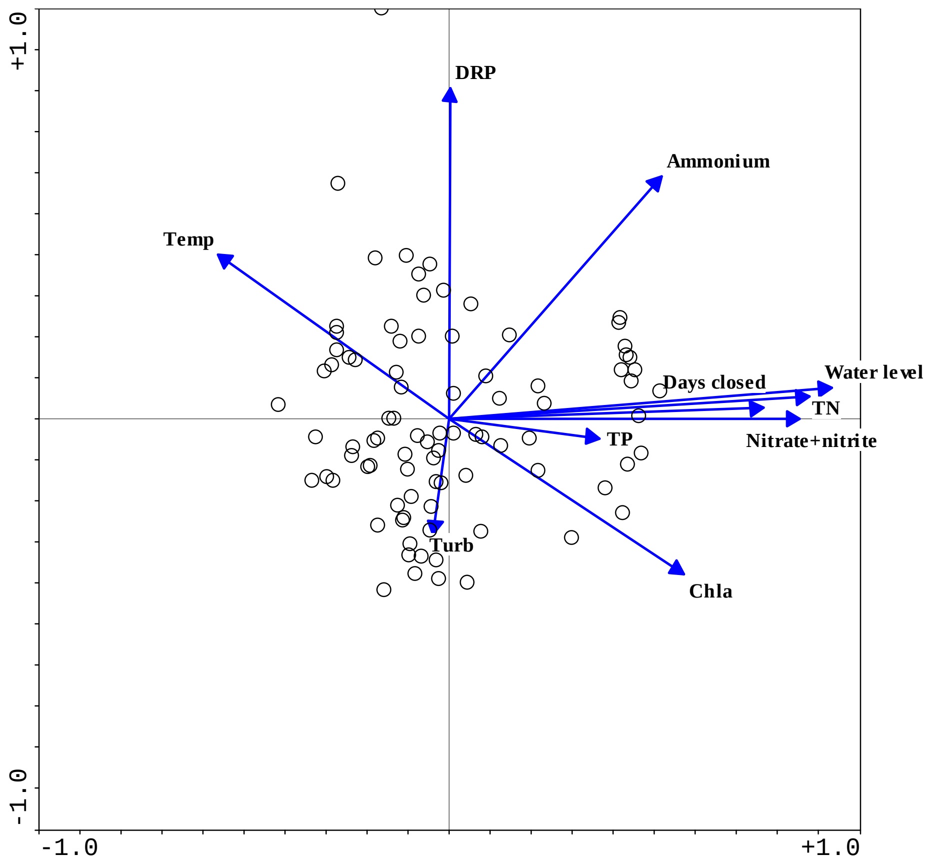

Figure 7. Principal components analysis of variables describing water quality and the opening regime of Waituna Lagoon. The primary axis (x-axis) explained 40% of the variation in the data. The secondary axis (y-axis) explained 14% of the variation in the data. The arrows represent the loadings (correlations) of the variable with the primary and secondary axes. The circles show the locations of the water samples in the ordination space.

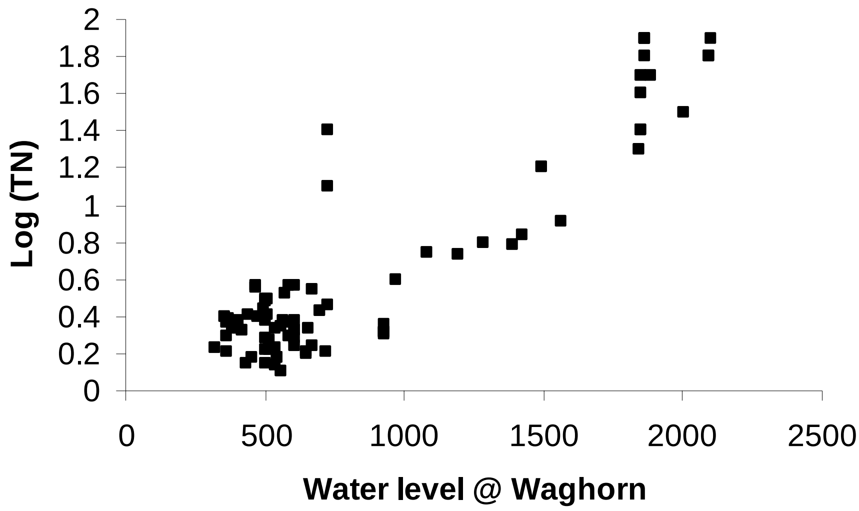

Figure 8. Correlation between water level and total nitrogen in Waituna Lagoon.

2. Axis 2 (y-axis) explained an additional 14% of the variation in the data. This axis was mainly driven by dissolved reactive phosphorus and ammonium concentrations and was independent of water level and opening/closing of the lagoon. A weak opposite loading by turbidity seems to suggest that this axis is related to wind resuspension, but turbidity was not significantly correlated to either DRP or ammonium ($P > 0.05$). At this stage it is not clear what process drives this second axis of variation.

3. Chlorophyll *a* concentration (an index of phytoplankton biomass) was weakly positively related to axis 1 (water level, TN) and weakly negatively related to temperature, indicating phytoplankton biomass increased with lagoon closure (days closed, R^2=0.10, P =0.003), water level rise (water level, $R^2 = 0.22$, $P < 0.0001$), increased nitrogen concentrations (TN, R^2 =0.29, $P < 0.0001$), and lower temperatures ($R^2 = 0.11$, P =0.003). Dissolved inorganic nitrogen and nitrate+nitrite concentrations were also significantly positively correlated with chlorophyll *a,* though not as strongly as TN. Neither DRP nor turbidity was significantly correlated to chlorophyll *a* ($P > 0.05$).

The positive correlations of chlorophyll *a* with both TN and nitrate+nitrite indicate that nitrogen availability does not constrain phytoplankton growth in Waituna Lagoon - it is generally above the concentration saturating phytoplankton growth. If nitrogen were always limiting phytoplankton growth, concentrations of dissolved inorganic nitrogen would tend to be very low in the lagoon and no covariance with chlorophyll *a* would be observed. On the other hand, the lack of correlation between chlorophyll *a* and DRP suggests that DRP may limit phytoplankton growth, at least when DRP concentrations are very low in the lagoon.

This interpretation is supported by examining the ratio of DIN (dissolved inorganic nitrogen):TP, which is a useful indicator of nitrogen and phosphorus limitation in lakes (Morris & Lewis 1988; M. Schallenberg, unpublished data). Analyses of a wide range of phytoplankton nutrient limitation bioassays from lakes around the world indicates that phytoplankton communities in lakes are likely to be nitrogen limited when the natural log (Ln) of the ratio of DIN:TP is negative, and phosphorus limited when the ratio is positive. The ratio in Waituna Lagoon tends to be positive (Fig. 8), indicating the potential for low phosphorus availability to constrain phytoplankton growth in the lagoon.

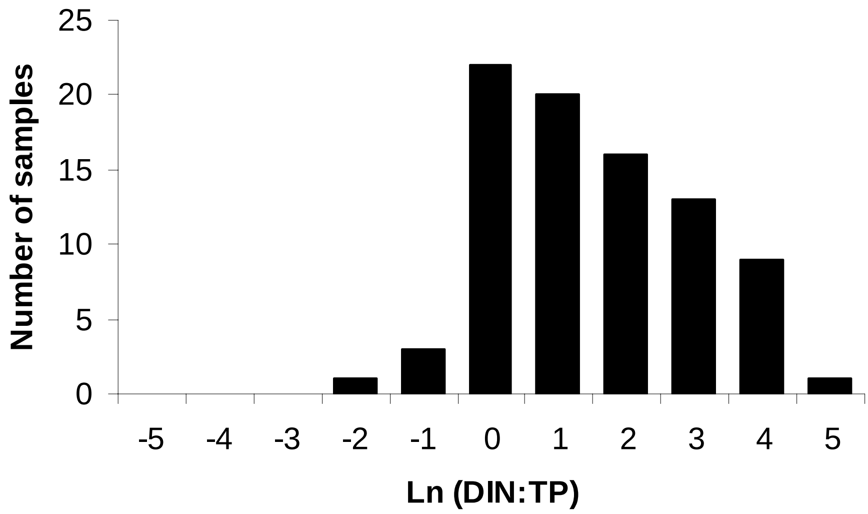

Figure 9. Number of samples showing various ratios of dissolved inorganic nitrogen: total phosphorus. Ratios above 0 show potential for phosphorus limitation of phytoplankton growth. Ratios below 0 show potential for nitrogen limitation of phytoplankton growth.

4. The apparent lack of importance of turbidity in the lagoon is surprising given how windswept the lagoon is, and how variable the water levels are. However, water quality sampling was generally conducted during calm weather (M. White, Environment Southland, pers. comm.),

biasing the sampling against recording the full range of variation in turbidity. Perhaps all that can be said from this analysis is that turbidity seems to decline rapidly (hours to days) after wind events cease, as has been observed in other shallow lakes (Hamilton 1989, Schallenberg & Burns 2004).

5. The importance of the lagoon opening/closing regime to water quality is confirmed in Fig. 10, where the sites are again plotted in the PCA ordination space, but this time they are coded with regard to whether the lagoon was open or closed when the samples were taken. This clearly shows that when the lagoon was open, water temperatures, nitrogen and chlorophyll *a* concentrations tended to be lower than when the lagoon was closed (see also Fig. 7). According to this analysis, lagoon opening/closing had little or no impact on turbidity or DRP concentrations.

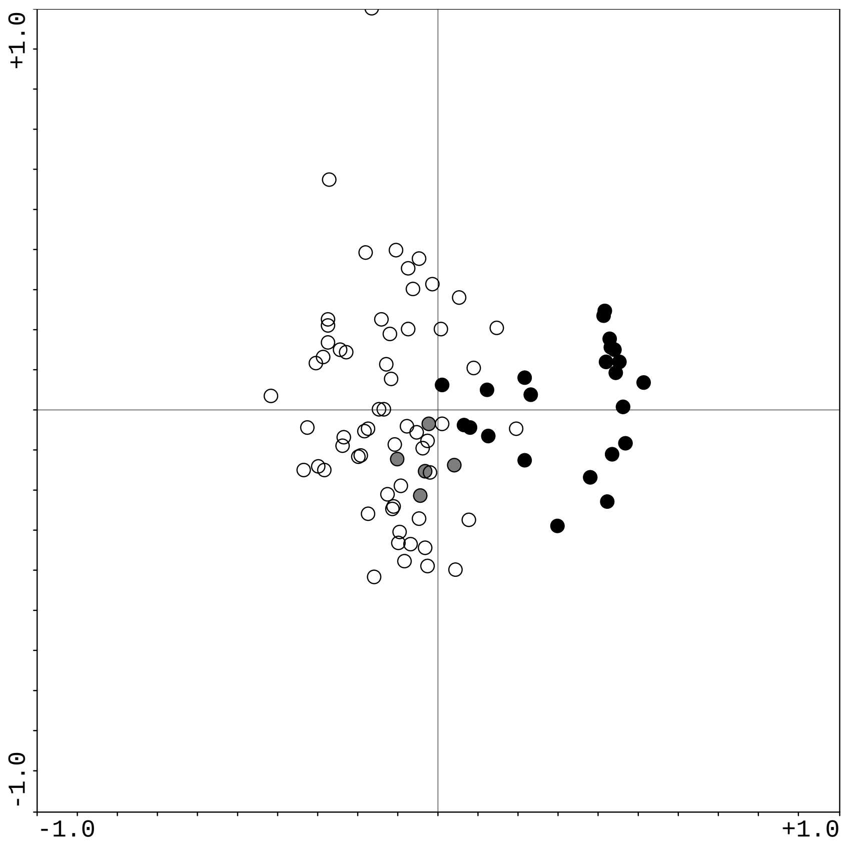

Figure 10. Locations of water samples in PCA ordination space (see Fig. 6), taken when the lagoon was open (open circles) and closed (black and grey circles). Grey circles represent samples taken when the lagoon was closed but water level was < 1.0 m on the staff gauge, indicating recent closure.

Our analysis of water quality data indicates that concentrations of available phosphorus may limit phytoplankton productivity at times in the lagoon. Therefore, at present, any phosphorus entering the lagoon can potentially fuel rapid phytoplankton growth when light and temperature conditions are also favourable, because nitrogen concentrations are surplus to demand. In the short term, strict controls on phosphorus may be the most effective way to prevent phytoplankton proliferation in the lagoon. Furthermore, controls on nitrogen inputs should also be considered, at least in the medium term, to bring levels down to where nitrogen availability may also exert control on phytoplankton. However, strongly reducing the nitrogen: phosphorus ratio (DIN:TP <

1) would not be desirable because it would favour cyanobacteria over the present phytoplankton community. Cyanobacteria are able to fix atmospheric nitrogen and thereby have a competitive advantage over other algae when the supply of nitrogen available to algae is depleted (Smith 1983). Cyanobacteria can: i) reach very high biomasses; ii) regulate their buoyancy; iii) cause severe light-limitation of macrophytes; iv) cause unsightly and smelly surface scums; and, v) potentially produce toxic compounds.

Unfortunately, there is insufficient data on the light climate in the lagoon to determine whether phytoplankton might be light-limited at times. Furthermore, data on zooplankton grazers would be useful in determining whether grazing pressure might be sufficient to control phytoplankton growth. For example, if zooplankton grazing played a significant role in controlling phytoplankton in the lagoon, then it might be useful to manage the lagoon in a way that doesn't negatively impact the main grazing taxa. Many factors can potentially contribute to controlling phytoplankton proliferation. The analyses presented here represent a first attempt to understand the phytoplankton ecology of the lagoon. More research is required (see recommendations) so that phytoplankton blooms, which often plague similar systems elsewhere (Gerbeaux 1989: Scheffer 1998), can be avoided.

5. Threats to macrophyte growth

Information presented above indicates that aquatic macrophytes are an important component of the foodwebs of Waituna Lagoon, and that they not only represent significant natural character of the lagoon but also play an important role in regulating water quality. The dominant macrophyte in the lagoon, *Ruppia* sp., is an important species in the lagoon ecosystem, fuelling invertebrate production, regulating water quality and phytoplankton growth, and providing habitat for fish and invertebrates. Indeed, *Ruppia* in this context could be considered a keystone species, whose ecological importance is disproportionate to its moderate abundance in the lagoon.

Whole-scale collapse of macrophyte communities followed by shifts to persistent phytoplankton dominance has been reported for many shallow lakes and lagoons in New Zealand (e.g. Gerbeaux 1989) and elsewhere (Scheffer 1998). A number of environmental stressors have been implicated in causing the macrophyte collapse, including wind events (Gerbeaux 1989), excess nutrient loading, decreased light penetration, and increased water levels (Scheffer 1998), sediment oxygen depletion (B. Sorrell, NIWA Christchurch, pers. comm.), and overgrazing by waterfowl (Mitchell *et al.* 1988). Salinity is another factor which stresses macrophyte physiology, potentially contributing to the collapse of macrophyte communities (Gerbeaux 1989). All of the above factors are threats to the macrophyte community of Waituna Lagoon, potentially acting synergistically and incrementally.

Light penetration is a key factor promoting macrophyte growth and health. Below, we present a simple conceptual model of light penetration into Waituna Lagoon, to explore how changes in water clarity and water levels could affect the future of the macrophyte population in the lagoon. Unfortunately, there were virtually no data available on light penetration or water clarity in the lagoon (e.g. only three Secchi disk readings). Therefore, we measured the underwater light climate at three sites in the lagoon (June 25, 2006). These measurements, along with water level data and a surface area vs. water level relationship (supplied by Environment Southland) formed the basis of our preliminary analysis.

Figure 11 illustrates how the simple model was constructed. It was first necessary to calculate the offset between the Waghorn staff gauge and mean sea level because the lagoon area vs. water level data supplied by Environment Southland were relative to mean sea level. We took mean sea level (MSL) to be the mean water level of the lagoon when it was open (data points influenced by seiches and floods were removed). The reading on the Waghorn staff gauge which corresponds to this measure of MSL is 510 mm.

Depth profiles of photosynthetically active radiation (PAR) were analysed to yield underwater PAR attenuation coefficients, which were then used to calculate the depth to which 1% of surface light penetrated into the lagoon. This depth is known as the Euphotic Depth, which estimates the depth below which there is insufficient light for plants to maintain their biomass. In other words, the Euphotic Depth (Z_{eu} = 1.8 m) is a rough estimate of the depth of the lower limit of plant growth for Waituna Lagoon, relative to the lagoon's surface.

The model (Fig. 11) is a stylised representation of Waituna Lagoon and the basic parameters of the light model. Assumptions of the model are presented in Table 5.

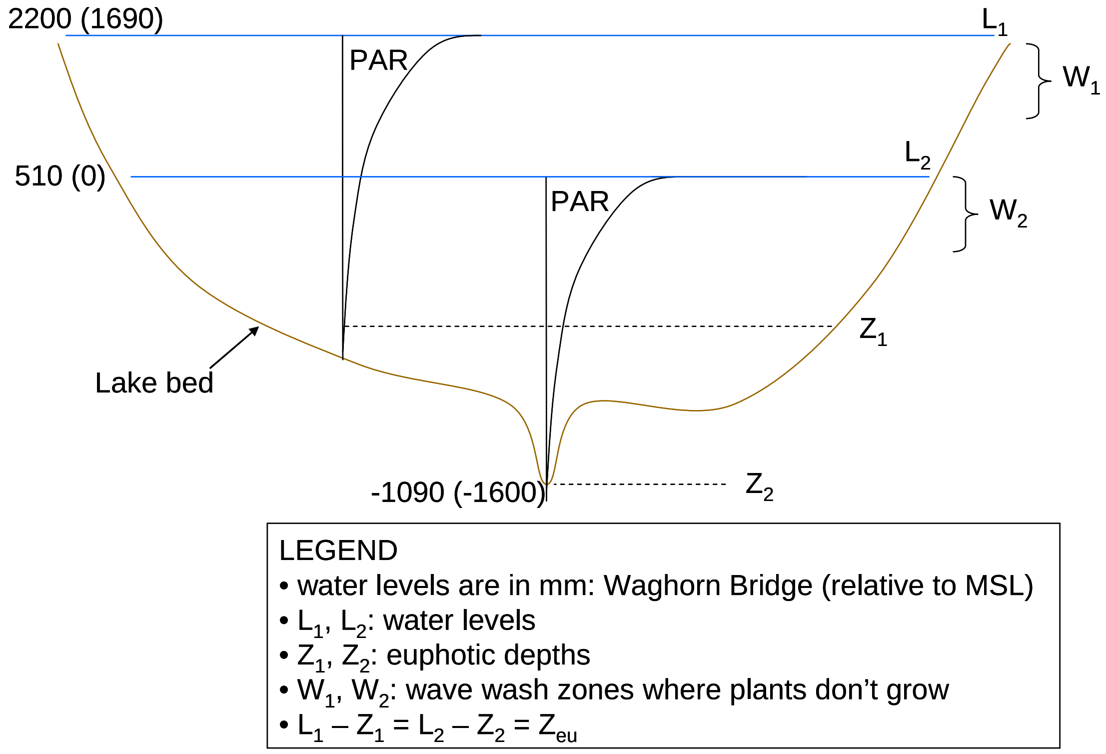

Figure 11. Structure of the light model used to estimate the distribution of light and potential zones of macrophyte growth in Waituna Lagoon.

Table 5. Assumptions related to the light model.

Assumption	Comments
1. As Waituna Lagoon is open for a substantial period of each year (Fig. 2) it was assumed that no macrophytes can grow above the lower MSL wave wash zone (L_2 - W_2).	Assumption likely to be realistic as even short-term desiccation kills *Ruppia* (Nicol 2005)
2. W_1 = 550 mm	Assumption based on seiche amplitudes measured in Waituna Lagoon (350mm; Jackson *et al.* 2001), and a wave wash zone reported for wind-swept Lake Alexandrina, Canterbury (700 mm; Ward & Talbot 1984).
3. W_2 = (mean tidal amplitude ÷ 2) + W_1 = 660 mm	Probably an underestimate of the macrophyte-free zone for the open lagoon because it does not account for turbulence due to tidal and density currents
4. PAR attenuation coefficient and euphotic depth does not vary with lagoon level (depth)	Likely to be false because sea water and humic-stained freshwaters have very different optical properties. However, when the lagoon is open, there is probably a greater tendency for sediment resuspension. Any reduction in sediment resuspension as the lagoon fills is likely to be somewhat offset by greater light absorbing characteristics of humic-stained freshwaters.

Levels indicated in the modeled scenarios below are relative to the Waghorn staff gauge, unless otherwise stated.

Scenario 1: Permanently open

If the lagoon were permanently open, then L_2 = 510, W_2 = 660, and Z_2 = -1290. The upper limit of macrophyte growth would be equal to L_2 - W_2 = -150 mm, and the lower limit would be Z_2 = -

1290 mm (below the deepest part of the lagoon bed). This scenario provides sufficient light for plants to grow on c. 3 km^2 of lagoon bottom.

Scenario 2: Permanently at 2200 mm (current maximum permitted level)

Under this scenario, L_1 = 2200, W_1 = 550, Z_1 = 400 mm. The upper limit of macrophyte growth would be equal to L_1 - W_1 = 1650 mm, and the lower limit would be equal to Z_1 = 400 mm. This scenario provides sufficient light for plants to grow on c. 5.9 km^2 of lagoon bottom.

Scenario 3: Varies between 510 mm (MSL) and 2200 mm (current operating range)

Under this scenario, the upper limit of macrophyte growth would be equal to L_2 - W_2 = -150 mm because desiccation would prevent plant growth above L_2. The lower limit of plant growth would be determined by the depth of light penetration relative to 2200 mm, because sufficient light would not penetrate below that depth when the lagoon is at 2200 mm. Therefore, the lower limit would be Z_1 = 400 mm, which is higher than the upper limit of growth determined by wave wash and desiccation. In this situation, there is an apparent light deficit equivalent to 550 mm of water depth.

Obviously, the model is an oversimplification of the lagoon system as it functions at present. It does not account for plant height or for the ability of plants to survive temporary periods of insufficient light by respiring their energy reserves. *Ruppia megacarpa* stems have been reported to grow up to 2 m long in Australian lagoons (Nicol 2005). Vertical growth is a useful adaptation for light harvesting in aquatic macrophytes. Nevertheless, heavy grazing by waterfowl (Gerbeaux 1993; Burrows 1994) and sudden increases in water level and/or turbidity can cause macrophytes to suffer light limitation. Based on our model, under Scenario 3, only plants > 550 mm tall would be able to survive in a narrow band below a level of -150 mm. Maximum length of Ruppia observed in our samples was c. 500 mm.

Studies have shown that healthy plants can survive temporary periods of insufficient light (e.g. <6 months for deep water charophytes; Howard-Williams *et al.* 1995) by respiring stored energy. The ability to survive by this mechanism is dependent on many factors including the health of the plant (energy reserves) and the water temperature. This introduces two more important variables affecting the growth and survival of macrophytes, namely the timing and duration of periods of light stress. Detailed data on *Ruppia* physiology would be required to accurately estimate the survival times of *Ruppia* in Waituna Lagoon under light stress. Such data are not available. Therefore, the simple light model we developed is conservative with regard to predicting the survival, growth and sustainability of macrophytes already growing in Waituna Lagoon. The model more accurately illustrates the capacity of the lagoon to regenerate aquatic macrophytes under various scenarios, if they were lost from the system.

Variation in water levels constrains macrophytes by confining areas of potential growth to a zone between the lowest water level and the depth where light limitation causes plants to die off. To further explore the effect of water level variation on potential plant distributions, we used the model to assess two more scenarios, representing regimes with restricted variations in water levels.

Scenario 4: Varies between 510 mm (MSL) and 1800 mm.

Under this scenario, the upper limit of macrophyte growth would be equal to L_2 - W_2 = -150 mm because desiccation would prevent plant growth above L_2. The lower limit of plant growth would be defined by the depth of light penetration relative to 1800 mm. Therefore, the lower limit would be Z_1 = 0 mm, producing a light deficit equivalent to 150 mm.

Scenario 5: Varies between510 mm (MSL) and 1400 mm.

The upper limit of macrophyte growth would be equal to L_2 - W_2 = -150 mm because desiccation would prevent plant growth above L_2. The lower limit of plant growth, defined by the depth of light penetration relative to 1400 mm, would be Z_1 = -400 mm, resulting in a zone of sufficient light between -150mm and -400mm, equivalent to c. 2 km^2 of lagoon bottom.

Table 6. Estimated area of lagoon bottom receiving sufficient light to grow macrophytes. Light deficit is the difference between the lower and upper limits of growth. Predictions are based on light availability only, and do not take into account salinity, substrate or other factors.

Scenario	**Estimated area** (km^2)	**Light deficit**
1. Permanently open	3.0	
2. Permanently closed, level at 2200 mm	5.9	
3. Level fluctuates between sea level and 2200 mm	0	-550 mm
4. Level fluctuates between sea level and 1800 mm	0	-150 mm
5. Level fluctuates between sea level and 1400 mm	2.0	

We reiterate that the light model presented here is a preliminary attempt to demonstrate how variations in lagoon water levels and water clarity together determine the light climate in the lagoon, and how the light climate, together with the lagoon's bathymetry, determine the area of lagoon bottom receiving sufficient light for plant growth. The model is based on the assumptions outlined in Table 5. It does not account for plant height or the use of stored energy (Howard-Williams *et al.* 1995) to sustain macrophytes through periods of high water level, when light is likely to be limiting. However, the model is useful in illustrating that the distribution of macrophytes in the lagoon is strictly confined by water clarity and the opening regime. ***It also shows that if the lagoon were to lose its macrophyte community, light limitation and desiccation would prevent the regrowth of macrophytes under present environmental conditions and water level management.***

6. Risk of Waituna Lagoon 'flipping' to algal dominance

There is a vast limnological literature (much of which is summarised in Scheffer 1998) concerning the predominance of two alternative states of shallow lakes and lagoons. The states are characterised by either: i) dominance by aquatic macrophytes, low biomass of phytoplankton, high biomass of zooplankton grazers, clear waters and high light penetration; or, ii) plankton dominated, turbid, and sparse or absent macrophytes. In general, the plankton-dominated state is considered undesirable because of the low water quality and low recreation (fishing, hunting, swimming and boating) and conservation values (lower taxonomic diversity, dominance by species of lower conservation value). Furthermore, the risk of harmful (i.e. toxic, smelly) cyanobacterial blooms is much greater in a plankton-dominated state.

Some lakes and lagoons are known to undergo changes from one state to the other on a regular basis (e.g. usually every few years: Tomahawk Lagoon #2; Mitchell *et al.* 1988). Others are known to have undergone a switch from macrophyte dominance to plankton dominance that has lasted decades (e.g. Waihora/Ellesmere, Canterbury), with the ecosystem apparently stable in its plankton-dominated state (Gerbeaux 1989; Scheffer 1998). Stability (or hysteresis) is also suggested for the macrophyte dominated state, such that either state has a number of internal ecological feedbacks in operation which serve to maintain the state until changes are imposed on the system which overwhelm these homeostatic processes, leading to a change or "flip" to the alternative stable state (Scheffer 1998). This threshold-like behaviour creates difficulties for managing and restoring such systems, once they flip to an undesirable state. For example, where high nutrient inputs from the catchment have been implicated as the cause for shifts to plankton dominance, nutrient concentrations have had to be reduced far below the levels that existed in the lake/lagoon prior to the shift to plankton dominance in order to return the system to a macrophyte dominated state. Often additional management strategies were required such as biomanipulation (fish population regulation) to encourage zooplankton grazers, and water level manipulation to enhance light penetration to the lake/lagoon bed (Scheffer 1998).

In New Zealand, Waihora/Ellesmere is a well-known example of a lake that has undergone a shift from macrophyte dominance to a persistent state of phytoplankton dominance. A key driver of this change was the Wahine storm of 1968, which uprooted much of the macrophyte biomass (predominantly *Ruppia megacarpa* and *Potamogeton pectinatus*) in the lake (Hughes *et al.* 1974; Gerbeaux 1989). The four main reasons listed by Gerbeaux (1989) for why the macrophyte beds had not re-established in Waihora/Ellesmere since 1968, were:

1) Insufficient light reaching bed of lake, due to suspension of sediments and phytoplankton.
2) Seeds of species such as *Ruppia* need freshwater or near freshwater conditions to germinate, and moderately saline conditions are now prevalent in the lake.
3) Movement of lake bed sediments frequently dislodge any seedlings that do germinate.
4) When water levels are high, seedlings can establish in sheltered bays, but if the lake is open to the sea for a long time, the lake bed dries out and the aquatic plants die.

Burrows (1994) suggested overgrazing by swans to be another factor, and recommended a substantial swan cull, and an increase in the maximum lake level by at least 1 m in order for submerged plants to recover.

The example of Waihora/Ellesmere is highly relevant to Waituna Lagoon because the systems share a number of important characteristics:
1) They are barrier-type lagoons which are artificially opened
2) They are brackish
3) *Ruppia* was/is a dominant component of the macrophyte communities in both
4) They have catchments which have experienced increasing intensity of agriculture
5) They are subject to high winds
6) They are important waterfowl habitats.

Factors unfavourable to macrophyte growth threaten the macrophyte-dominated state of Waituna Lagoon. Such factors include increases in:
1) Nutrient loading to the lagoon (favours phytoplankton and epiphyton (see glossary) growth)
2) Sediment loading to the lagoon (decreases light penetration)
3) Variability in water levels (see Section 5)
4) Grazing by waterfowl (reduction in plant height and capacity to harvest light)
5) Salinity (*Ruppia* does not germinate under strongly saline conditions (Gerbeaux 1993, Nicol 2005) and optimum salinities for *Ruppia megacarpa* growth are reported to be between 4 and 8 ppt; Gerbeaux 1989)
6) Wind (see Section 7)

An increase in lagoon siltation has been noted by Raymond Waghorn (pers. comm., cited by Johnson & Partridge 1998): "The late 1960's, a time of increased drainage of farmland, also saw increased siltation within the lagoon... Fishing holes formerly present at mouth of Waituna Creek, and at the mouth of Shand Bay are now gone, all silted up. In 1974 a digger took the Currans Creek drain up beyond the initial 1 km. Silt then flowed into the lagoon, whereas in previous times it had been trapped in the swamp."

Increasing sediment and nutrient loading have been identified as issues of concern for Waituna Lagoon (Thompson & Ryder 2003). Other threats are covered in this report.

Waihora/Ellesmere has been described as ecologically "dead" in a recent newspaper article (Environment Court Judge John Smith, as reported in the Christchurch Press, August 24, 2005). Waituna Lagoon has not yet flipped to a phytoplankton dominated state, but is at risk of doing so in light of the issues discussed in this report. The alternative state, as illustrated by Waihora/Ellesmere, is not desirable and, based on experiences elsewhere, restoration would be difficult, costly, and might not succeed for decades (Scheffer 1998).

7. Potential impacts of climate change and sea-level rise on aquatic macrophytes in Waituna Lagoon

Climate change

Global climate change is predicted to result in diverse regional-scale changes to climate and sea level. Climate change maps generated from downscaled global circulation models indicate that the southern part of South Island will experience greater westerly and south-westerly air flows (Mullan *et al.* 2001), with increasing southerly storms and associated precipitation. The prevailing winds at Waituna Lagoon are from the west (Department of Lands and Survey 1984), and climate change is expected to exacerbate present climate forcing in the region. For example, ***Waituna Lagoon will experience higher westerly and southwesterly wind speeds, more windy days, and higher levels of precipitation and runoff due to southerly fronts.*** These climate changes can be expected to exacerbate current threats to the plant community of the lagoon by:

1) Increasing the risk of severe wind events, which could uproot aquatic macrophytes,
2) Increasing sediment resuspension in the lagoon, thereby decreasing light penetration,
3) Increasing runoff and associated loadings of nutrients and sediments from the catchment; and,
4) Increasing the rate of water level rise in the lagoon.

The reliability of regional climate models is fast approaching the level whereby output data from the models could be used to predict specific environmental change in the lagoon, and other ecosystems. Therefore, it would be useful to develop models that relate key environmental factors to important ecological attributes, such as macrophyte community health. In this way, it would be possible to make predictions of the ecological outcomes of climate change, information which is critical to the sustainable management of ecosystems, habitats and species.

Sea Level

In the past century, sea levels around New Zealand rose at an average rate of 2.1 mm y^{-1} (Hannah 2004). The Intergovernmental Panel on Climate Change (IPCC) predicts that the rate of sea level rise in this century (to 2100) will be between 2 and 7 mm y^{-1} (IPCC 2003). This range is now considered to be conservative, and revised sea level curves will be published in the next IPCC report in 2007. Sea level is an important variable in the functioning of Waituna Lagoon because it determines the water level of the open lagoon, the salinity of the open lagoon, and the dynamics of coastal sediment transport (Shennan 1993; Nichol *et al.* 1997), which influences the sediment budget of the lagoon.

Salinities above c. 8 ppt slow the growth of *Ruppia* spp., and seed germination and seedling establishment require periods of low salinity, approaching that of freshwater (Gerbeaux 1989; Nicol 2005). A rising sea level may threaten growth and recruitment of the macrophyte community in the lagoon due to salinity, but might also result in a reduction in the water level variation of the lagoon which would favour macrophyte growth (Section 5).

Perhaps the greatest longer-term concern regarding sea level rise will be the change in coastal geomorphology, which has been shaped by a relatively stable sea level for the past c. 7000 years (Gibb 1986). The increased wave energy that will impinge on the coastline will result in net inland movement of sediments and restructuring of coastlines and coastal environments (e.g. Nichol *et al.* 1997). Even now, the gravel barrier enclosing Waituna Lagoon is moving inland at a rate which results in an estimated loss of 0.62 ha of lagoon per year (Kirk & Lauder 2000). It seems reasonable that the predicted acceleration in sea level rise will exacerbate this process, filling the lagoon with sand from the marine entrance. ***Therefore, on the scale of decades to centuries, the main threats to the lagoon will be geomorphological and the long-term survival of the lagoon will depend principally on the relative rise in sea level vs. the rate of sediment infilling of the lagoon from terrestrial and marine sources.*** Artificial opening of the lagoon also depends upon a coincidence of spring (low) tides and a calm sea. If these conditions are not met, opening may be delayed by one or more months, during which time rain can bring the lagoon level considerably higher (up to 3.45 m in 1994). Therefore, sea level rise over a period of decades is likely to affect the opening regime of the lagoon.

8. Aquatic macrophytes in Waituna Lagoon: a temporal and geographical context

Waituna-type lagoons in New Zealand are an ephemeral coastal feature in geological time. Seven Waituna-type lagoons developed from estuaries in the South Island within the past 4000-6000 years, but are being progressively reduced in both area and in number, by coastal erosion and sometimes by human activities (Kirk & Lauder 2000). Historically most of these lagoons had much higher water levels (average and ranges), and therefore greater areas and volumes of water. Natural openings were rare and short-lived, and were due to a combination of increased water levels and winds creating a hydraulic head that could breach the enclosing barrier. Being closed and freshwater most of the time was a characteristic essential to their productivity, particularly in terms of biomass of aquatic plants and ability to support waterfowl.

Naturally fluctuating water levels in Waituna and Waihora/Ellesmere are considered, on the one hand, to be a major factor contributing to the outstanding conservation values of these lagoons and their surrounding wetlands (Department of Lands and Survey 1984; O'Donnell 1985; Williams 1980), and, on the other, to be a threat to agricultural development. Water levels in most Waituna-type lagoons are currently managed to control flooding and/or facilitate drainage of adjacent farmland, resulting in reduced water levels, smaller variation of levels and reduced lagoon surface area and volume. Control mechanisms include: direct excavation (Waituna and Waihora/Ellesmere); 'box' structures (Wainono); culverts or pipes (Cooper's Lagoon); or by maintaining beach crests to ensure breakouts in floods (Washdyke Lagoon; Kirk & Lauder 2000).

Of these, the water level management regime at Waihora/Lake Ellesmere is the most similar to that of Waituna (Table 7), with regular artificial openings since 1887, although Waihora/Ellesmere spends more time closed than Waituna. The average number of openings per year increased from 1.59 y^{-1} (in 1913-1947) to 3.46 y^{-1} (in 1947-1987), while over the same periods, the average duration of opening decreased from 42.5 d to 23 d (sourced from Gerbeaux 1993). This is the direct opposite to the experience at Waituna Lagoon, where the trend has been to have fewer openings of longer duration. The shorter duration of opening at

Waihora/Ellesmere is due to more active coastal processes, with wave action and longshore gravel movements closing the outlet more frequent than at Waituna (Kirk & Lauder 2000).

Table 7. Current artificial opening regimes for Waituna-type coastal lagoons. Sources: Lake Waituna Control Association (Waituna); Lake Settlers Association (Waihora/Ellesmere). *Data unavailable for 2000-2001.

Lagoon	Period	Mean opening frequency	Trigger level (a.s.l.)	Duration mean (range)
Waituna	1992-2006*	0.9 / year	1.69 m (2.2 m staff gauge)	201 days (19-864)
Waihora/ Ellesmere	1981-1990	3.1 /year	1.05 m Sept-April 1.13 m May-Aug	18.2 days (4-76)

O'Donnell's (1985) review of the wildlife habitat of Waihora/Ellesmere stated that the optimum opening regime for birds was a gradual, not sudden, drop of water levels in summer, synchronised with waterfowl breeding. As noted in Section 3, suitable water level regimes are critical to the amount of aquatic vegetation available and therefore the successful breeding of water birds. ***From the point of view of restoring the aquatic macrophyte community, Gerbeaux (1993) argued that opening the lake in early spring was desirable to provide light to Ruppia seedlings, encouraging rhizomal propagation and firm rooting. This was to be followed by a higher water level in summer to protect the macrophytes from wave action and waterfowl grazing.*** It is clear from the Waihora/Ellesmere example that competing interests exist, with different proposals for water level management

Another Waituna-type lagoon is Wainono Lagoon in South Canterbury, where the control of maximum water levels in the lagoon used to be via the Waihau Box, where water exited to the sea when the box was open, and seeped through the fore dune when the box was closed. Under this regime, Pierce (1980) observed Wainono Lagoon to be normally very shallow, averaging about 1.0 m depth, with very high water levels being 1.5 m a.s.l. and never exceeding 2 m. Salinity varied from 5-25% but was usually less than 10%, as evidenced by the composition of the aquatic plant community: *Myriophyllum sp. Lilaeopsis novaezealandiae, Ruppia megacarpa* and *Ranunculus* sp. (Pierce 1980). Very low water levels (< 0.6m a.s.l.) during droughts in

August-December 1969 and for two months in autumn 1973, in combination with strong winds, kept the lagoon continuously turbid. In April 2004, the lagoon was very turbid with a maximum water depth of 0.25 m (M. Schallenberg pers. obs.). Unfortunately, we have no further information on Wainono and are therefore unable to state the relevance of its opening regime to the Waituna Lagoon situation.

Temporarily-open estuaries or coastal lagoons are found around the world (e.g. Australia, India, South Africa, South America and the USA). They usually differ in several key respects to the Waituna-type lagoons found in New Zealand, but do share the characteristic of being the estuary type most sensitive to human activities (Whitfield 1992; Haines *et al.* 2006).

About 70% of South Africa's coastal estuaries are classed as temporarily open/closed systems (Whitfield 1992) which tend to be small, with no freshwater flows during the dry season, and only open rarely in the wet season due to natural breaching. Therefore, they probably have limited relevance to Waituna Lagoon.

Artificial opening of coastal lagoons in Brazil, involving deliberate sand bar breaching by local authorities, have usually been made in order to decrease the nutrient and sediment loads associated with the discharge of non-treated domestic sewage into the lagoons. Studies of openings of these shallow tropical lagoons (Palma-Silva *et al.* 2002; dos Santos *et al.* 2006), demonstrated that occasionally the lagoons flipped to phytoplankton dominance after brief openings, due to nutrients released from aquatic plants that had been killed by saltwater (dos Santos *et al.* 2006). We consider that these studies have little relevance to Waituna Lagoon.

Gobler *et al.* (2005) was the first peer-reviewed study of a temporarily open estuary in the USA; Mecox Bay in Long Island, New York State. An outlet connecting Mecox Bay to the Atlantic Ocean is dredged several times a year, to control water levels and prevent coastal flooding of homes surrounding the bay, although openings also help to flush nutrients and to maintain salinity within the brackish range required by resident shellfish (Gobler *et al.* 2005). Depth and salinity were the parameters most obviously affected by openings, but levels of chlorophyll *a* increased after opening, suggesting that the net growth of phytoplankton was higher than export rates to the sea. Light was not limiting in this system, and phosphate import from the sea and dilution of zooplankton grazers were considered to be responsible for the increased algal biomass (Gobler *et al.* 2005).

In Australia, management is being developed for coastal lagoons (termed ICOLL - intermittently closed and open lake or lagoon) to take into consideration their variable connections to the sea, and the effect that these have on water quality, aquatic habitat structure and a range of environmental processes (Haines *et al.* 2006). Some of these lagoons are Waituna-type, with similar waterfowl and flora (e.g. *Ruppia* spp.), although they experience different rainfall patterns, and evaporation is a major route of water loss. More than half of the 78 or so ICOLLs on the NSW coast are artificially opened from time to time, usually in order to avoid flooding of fringing public and private lands. ***However, in their assessment of ICOLL sensitivity, Haines et al. (2006) recommended against artificially opening an ICOLL at a level lower than the natural breakout range without thorough environmental investigation, as this may lead to more frequent openings, increased shoaling at the entrance, drying out, terrestrialisation of fringing wetlands and changes to macrophyte and benthic communities.***

Wilson Inlet, a coastal lagoon in Western Australia, is being studied as part of the National Eutrophication Management Program (http://www.rivers.gov.au/research/nemp/uwa17.htm, accessed July 28, 2006), to investigate the role of its main aquatic plant *Ruppia megacarpa* in nutrient cycling and in preventing algal blooms. Wilson Inlet has a regular annual cycle of artificial opening in late winter, staying open for approximately 5 months (between August-February). Results from the Wilson Inlet study should be of interest to the future management of Waituna Lagoon.

International data supports the key role that aquatic macrophytes play in maintaining healthy, coastal lagoon systems. Their role in nutrient cycling, providing food and habitat for aquatic fauna, minimising shore erosion, and keeping the water clear and free of potentially harmful phytoplankton blooms is supported by their robustness in surviving wide variations in salinity. Generally, Waituna-type lagoons were historically closed to the sea, with rare openings associated with flooding events (Kirk & Lauder 2000). The role of artificial opening regimes has generally been to ensure that high water levels associated with flooding are either avoided or minimised. Along with adapting to increasing salinity and depth variations, aquatic macrophyte communities are challenged by increases in nutrient and sediment loads to these systems.

Experience overseas and in Waihora/Ellesmere demonstrates that the loss of aquatic plants is a double threat because of the homeostatic role they play in moderating water quality and nutrient cycles; once lost, the lagoon may flip to a plankton-dominated state beyond which it may not be feasible to re-establish macrophyte beds.

CONCLUSIONS

1. The macrophyte, *Ruppia megacarpa,* is a keystone species in Waituna Lagoon because of its importance as a habitat for invertebrates and fish, as a food source for invertebrates and waterfowl, and because of its role in regulating water quality. The macrophyte community appears to be unique in New Zealand and is similar to that which existed in Waihora/Ellesmere prior to the Wahine storm of 1968.

2. The distribution of the macrophyte community in Waituna Lagoon is delineated by a lower depth threshold caused by light limitation and an upper growth limit regulated by wave wash and desiccation. Extended periods of high water are detrimental to the macrophyte community because the threshold of light limitation approaches the upper growth limit. However, the impact of this on *Ruppia* depends upon the resilience of *Ruppia* spp. to low light conditions in Waituna Lagoon.

3. Maintenance of high light conditions in the lagoon is essential to macrophyte survival. Therefore, high water levels should persist for less than 2 months to ensure macrophyte growth is not excessively light limited. Increases in phytoplankton biomass and/or suspended sediment concentrations will also reduce light penetration and reduce the habitat for macrophyte growth. Phytoplankton appear to be phosphorus limited at times. Therefore, the reduction of phosphorus availability in the lagoon currently represents the best means for controlling phytoplankton growth and biomass accumulation.

4. Since 1975, the opening regime has tended towards maintaining the lagoon in an open state for longer periods of time, probably resulting in higher mean salinities in the lagoon. As the optimum growth rates of *Ruppia* spp. are achieved between 4 and 8 ppt salinity, the opening regime may be maintaining *Ruppia* spp. at sub-optimal growth rates for increasing periods of time. *Ruppia* spp. seed germination and seedling establishment require periods of low salinity

(following closure). Periods of closure are important to ensure effective *Ruppia* spp. recruitment.

5. The various threats or stressors to the maintenance of *Ruppia* beds in the lagoon may result in catastrophic macrophyte loss, with subsequent establishment of an undesirable, stable phase of plankton dominance. Based on estimates from our light model, the present light climate and opening regime would not allow for the regrowth of *Ruppia* beds in the lagoon, if they were lost.

6. Climate change presents new potential threats to the macrophyte community. Increasing westerly and south-westerly winds are likely to uproot macrophyte communities and increase sediment resuspension in the lagoon. Increasing precipitation is likely to result in greater nutrient and suspended sediment inputs to the lagoon. Sea level rise will likely increase the salinity in the lagoon but also benefit the macrophyte community by potentially reducing water level variation in the lagoon. On the scale of decades, changes to coastal geomorphology will impact on the lagoon and its long-term sustainability will depend on the balance between sea level rise and increasing sediment inputs from both terrestrial and marine sources.

7. Published research on similar temperate lagoon systems in Australia and the USA is relevant to the Waituna Lagoon ecosystem. The history of Waihora/Ellesmere illustrates the serious consequences of ignoring the ecological processes in the lagoon, and of failing to sustainably manage these still poorly understood ecosystems.

RECOMMENDATIONS FOR THE SUSTAINABLE MANAGEMENT OF MACROPHYTES

1. Management:

i. Maintain or constrain water level variability. Duration of high water levels (estimated at 1800 mm on Waghorn staff gauge) should not exceed 2 months.

ii. Maintain or reduce nutrient and sediment loading to the lagoon (e.g. sediment trap technology). Currently, phosphorus reductions may be most effective at controlling phytoplankton proliferation.

iii. Until the salinity and light requirements for *Ruppia* spp. recruitment in Waituna are known, keep salinities low and light levels high during spring to optimise seed germination and seedling survival (i.e. where possible, keep the lagoon level low in spring and allow it to rise if possible in summer; see Gerbeaux 1993).

iv. Decrease the time that the lagoon is open (e.g. time per year) in order to reduce longer term saline influence, but maintain magnitude of salinity variations.

v. Monitor for and prevent overgrazing of aquatic macrophytes by waterfowl.

vi. Prevent the introduction of coarse fish, which may feed on aquatic macrophytes

2. Research and monitoring:

i. Conduct a detailed macrophyte survey of the lagoon to determine the community structure and distribution of macrophytes. This should carried out both while the lagoon is open and after it has been closed for at least 1 month (i.e. while water levels are relatively high). Initial surveys should be undertaken in summer.

ii. Include light/transparency, salinity and phytoplankton (dominant species and biomass) in monitoring programme (at least three sites). Depth profiles of salinity, oxygen and light should be taken.

iii. Study *Ruppia* spp. recruitment processes in Waituna Lagoon

iv. Exchange information with international groups working on similar problems and issues regarding macrophytes (esp. *Ruppia*) in coastal lagoons (especially those in Southern Australia).

v. Conduct a detailed survey to determine the distribution of sediment grain size and organic content in the lagoon, to determine the relationship between *Ruppia* presence/absence and sediment characteristics. This survey should coincide with one of the macrophyte surveys.

vi. Define and interpret ecosystem services provided by *Ruppia* (effects on water quality, food webs and habitat provision).

GLOSSARY

benthic - *related to the bottom sediment or substrate (e.g. plants, rocks) of a water body*
charophyte - *a group of aquatic macro-algae commonly known as stoneworts*
epiphyton - *aquatic microscopic algae which grow on solid substrates such as sediment, rocks, plants, etc.*
invertebrate - *animals with exoskeletons (without internal skeletons), including insects, molluscs, crustaceans, etc.*
macrophyte - *aquatic plants visible with the naked eye*
phytoplankton - *microscopic aquatic plants that live suspended in water, including algae and cyanobacteria*
plankton - *organisms which live in the water column*
seiche - *change in water level induced by wind*

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APPENDIX 1. Observations and data on the openings and closings of Waituna Lagoon since 1967. Based on Lake Waituna Control Association records (1972-1997); supplemented by information from files (Lake Waituna Outlet – Job B 435, details of opening costs, 1967-1976), and Environment Southland (2001-2006). All openings have been made at the western end of the lagoon (except where specified).

Date opened	Date closed	Level (m)	Days open
1967	-	-	-
September 1968	-	-	-
June 1969	-	-	-
November 1969	July 1970	-	-
5 October 1970	-	-	-
25 April 1972	31 May 1972	2.4	36
22 July 1972	8 August 1972	2.2	17
20 September 1972 East end	10 October 1972	2.2	20
8 June 1973	9 June 1973	–	1
16 June 1973			
16 July 1974	beaten by tide	–	–
17 July 1974	–	–	–
29 May 1975	19 June 1975	2.2	21
17 September 1975	10 November 1975	1.9	54
26 July 1976 Hansens Bay	23 August 1976	2.4	28
12 May 1977	6 June 1977	2.0	25
7 October 1977	3 November 1977	2.0	27
14 August 1978	10 October 1978	2.2	57
24 February 1979	1 July 1979	1.85	127
26 September 1979	22 March 1980	2.2	178
22 June 1980	27 June 1980	2.2	5
27 August 1980	30 October 1980	2.6	64
24 July 1981	8 September 1980	2.15	46
21 October 1981	26 April 1982	2.0	187
2 July 1982	18 July 1982	2.1	16

13 September 1982	3 October 1982	2.2	20
3 January 1983	30 June 1983	2.2	178
5 September 1983	1 June 1984	2.1	270
4 October 1984	1 May 1985	2.02	209
26 July 1985	17 September 1985	2.35	53
16 May 1986	8 June 1986	2.3	23
14 August 1986	4 May 1987	2.65	263
5 August 1987	23 August 1987	2.35	18
19 May 1988	19 July 1988	2.75	61
20 September 1988	8 March 1989	2.3	169
24 June 1989	10 June 1990	2.6	351
23 February 1991	1 June 1991	2.5	98
21 October 1991	23 May 1992	2.22	215
10 August 1992	24 October 1992	2.7	75
5 July 1994	5 September 1994	3.45	62
12 July 1995	31 March 1996	3.0	263
4 July 1996	15 January 1997	2.4	195
2 July 1997	21 July 1997	2.2	19
20 December 1997	2 May 2000	2.25	864
14 October 2000	-	2.27	-
10 June 2002	8 August 2002	2.30	59
9 November 2002	4 May 2003	2.30	176
24 July 2003	1 April 2004	2.20	252
10 June 2004	15 July 2004	2.20	35
5 January 2005	2 April 2005	2.20	87
7 July 2005	2 June 2006	2.00	330

APPENDIX 2. List of bird species recorded in Waituna Wetlands Scientific Reserve (from Department of Lands and Survey, 1984). Species are in taxonomical order. Naturalised bird species have been omitted from this list unless they are classed as waterfowl. Biogeographical status codes follow O'Flaherty (2005), with Waituna residency information from Thompson and Ryder (2003). N = native, E = endemic, I = introduced by human agency, M = migrant, R = resident, S = straggler (irregular visitor straying from its normal migratory path). Feeding habitat codes: farmland (F), lake (L), mudflats (MF), ponds (P), sea (SW), thickets (T); from Heather and Robertson (2000). National threat status is shown on right (Molloy et al. 2002), except for * = species listed by Cromarty and Scott (1996) as being of conservation concern.

Common name (scientific name)	Type	Feeding habitat	Status
Black shag (*Phalacrocorax carbo novaehollandiae*)	N, R	L	Sparse
Pied shag (*P. varius varius*)	N, R	L	Sparse
Little black shag (*P. sulcirostris*)	N, R	L	
Little shag (*P. melanoleucos brevirostris*)	E, R	L	
Stewart Island shag (*Leucocarbo chalconotus*)	E, R	L, SW	Nationally Vulnerable
White-faced heron (*Ardea novaehollandiae*)	N, R	L, P, MF, F	
White heron (*Egretta alba modesta*)	N, O	L, P	Nationally Critical
Little egret (*E. garzetta nigripes*)	O	L	
Cattle egret (*Bulbulcus ibis coromandus*)	M, O	F	
Australasian bittern (*Botaurus poiciloptilus*)	N, R	P, T	Nationally Endangered
Glossy ibis (*Plegadis falcinellus*)	S, O	MF, L, P	
Royal spoonbill (*Platalea regia*)	N, O	MF, L	
Black swan (*Cygnus atratus*)	I, R	L, P, MF, F	
Canada goose (*Branta canadensis maxima*)	I, R	L, P, MF, F	
Paradise shelduck (*Tadorna variegata*)	E, R	L, P, MF, F	
Chestnut-breasted shelduck (*T. tadornoides*)	S, M	L, P, MF, F	
Mallard (*Anas platyrhynchos platyrhynchos*)	I, R	L, P, MF, F	
Grey duck (*A. superciliosa superciliosa*)	N, R	L, P, MF	Serious Decline

Grey teal (*A. gracilis*)	N, M	L, P, MF, F	
Brown teal (*A. aucklandica chlorotis*)	E, O	L, MF	Nationally Critical
New Zealand shoveler (*A. rhynchotis variegata*)	E, R	L, P, MF	
Marsh crake (*Porzana pusilla affinis*)	N, R	T	Sparse
Spotless crake (*P. tabuensis plumbea*)	N, R	T	Sparse
Pukeko (*Porphyrio porphryio melanotus*)	N, R	MF, P, F	
South Island pied oystercatcher (*Haemotopus ostralegus finschi*)	N, R	MF, F	
Variable oystercatcher (*H. unicolor*)	E, R	MF, F	*
Pied stilt (*Himantopus himantopus leucocephalus*)	N, R	L, P, MF, F	
Southern NZ dotterel (*Charadrius obscurus obscurus*)	E, M	MF, P	*Nationally Critical
Banded dotterel (*C. bicinctus bicinctus*)	M	MF, P, F	*Gradual Decline
Mongolian dotterel (*C. mongolus mongolus*)	S, M	MF	
Wrybill (*Anarynchus frontalis*)	E, M	MF, P	*Nationally Vulnerable
Pacific golden plover (*Pluvialis fulva*)	N, M	MF, P, F	*
Grey plover (*P. squatarola*)	N, M	MF	*
Spur-winged plover (*Vanellus miles novaehollandiae*)	N, R	MF, P, F	
Turnstone (*Arenaria interpres interpres*)	M	MF	
Lesser Knot (*Calidrus canutus rogersi*)	O	MF	
Sanderling (*C. alba*)	S, M	MF, P	
Curlew sandpiper (*C. ferruginea*)	M	MF	*
Sharp-tailed sandpiper (*C. acuminata*)	M	MF, P	*
Pectoral sandpiper (*C. melanotos*)	M	P	
Red-necked stint (*C. ruficollis*)	M	MF, P	*
Far-eastern curlew (*Numenius madagascariensis*)	M	MF	*
Asiatic whimbrel (*N. phaeopus variegatus*)	M	MF	*
American whimbrel (*N. p. hudsonicus*)	S, M	MF	*
Eastern bar-tailed godwit (*Limosa lapponica baueri*)	M	MF	

Siberian tattler (*Tringa brevipes*)	S, M	MF	
Marsh sandpiper (*T. stagnatilis*)	S, M	MF, P	
Terek sandpiper (*T. terek*)	S, M	MF	*
Southern Black-backed gull (*Larus dominicanus dominicanus*)	N, R	F, SW	
Red-billed gull (*L. novaehollandiae scopulinus*)	N, R	F, SW	
Black-billed gull (*L. bulleri*)	E, R	L, P, MF, F	Serious Decline
Black-fronted tern (*Sterna albostriata*)	E, M	MF, L, P, F	Serious Decline
Caspian tern (*S. caspia*)	N	MF, L, SW	
White-fronted tern (*S. striata*)	N, R	SW	Gradual Decline
Eastern little tern (*S. albifrons sinensis*)	M	L, SW	
New Zealand kingfisher (*Halcyon sancta vagans*)	N, R	L, P, MF, F	
South Island fernbird (*Bowdleria puncata punctata*)	E, R	T	Sparse