Environment Canterbury Regional Council
Kaunihera Taiao ki Waitaha

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RECENT ENVIRONMENTAL HISTORY OF WAINONO LAGOON (SOUTH CANTERBURY, NEW ZEALAND)

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Executive summary

1. Wainono Lagoon is a coastal lake located on the east coast of New Zealand's South Island. The lake and its associated wetlands are of regional and national significance for waterfowl, other birds and native fish. These wetlands are mere remnants of what was once an extensive lowland coastal lake-wetland complex that, at the time of European colonisation, provided a diverse mahinga kai resource for hundreds of Māori inhabitants of the area. The lake is currently hypertrophic, with high levels of planktonic algae and turbidity. Nowadays, aquatic plants, which are common in shallow lakes and are beneficial to the ecology and water quality of lakes, are rarely observed in Wainono Lagoon.

2. This study was undertaken to determine the environmental history of the lake to help understand what the lake's natural, pristine condition was and to understand how and why it has changed in recent times. This information can be useful for management and restoration of the lake, particularly with regard to managing the effects of land use and hydrological modification on the lake's ecological and cultural values and on the ecosystem services it provides.

3. To investigate the recent environmental history of Wainono Lagoon, the contents of sediment cores spanning at least the last 160 years were analysed to determine environmental and ecological trajectories of the lake. A combination of historical information about the lake and its catchment and palaeo-limnological analyses were used for our analysis. Radioactive isotopes of lead and caesium were used to date the core. Remains of diatoms and macrofossils in the cores were used as environmental proxies.

4. Early European visitors described a vast quaking swampland between Willowbridge and the Makikihi River. Wainono Lagoon would have been part of this coastal wetland system. Both diatoms and macrofossil remains indicated that the lake was predominantly freshwater during this era. Remains of macrophytes (charophytes), freshwater sponges and freshwater zooplankton were also found in the sediments laid down at that time.

5. In the 1860s and 1870s major fires were recorded and most of the upland areas (areas excluding the wetland) were subject to fire-assisted conversion to pasture. This caused erosion of soils and an influx of fine and then coarse soil particles and charcoal to the wetland area. The lake continued to be a freshwater system with biological communities remaining more or less unchanged due to the buffering effect of the extensive fringing wetlands.

6. The second major anthropogenic influence on the system was the establishment of an artificial connection of the lake outflow with the sea in 1910 (the Waihao Box). This lowered water levels and introduced saline waters to the lake. Overtopping of the gravel barrier bar by the sea during extreme high seas caused substantial salinity variations because of the much reduced water volume of the lake-wetland complex. The new salinity dynamics caused a shift in the lake biota to more estuarine communities, including a replacement of the charophytes by the seagrass, *Ruppia* sp..

7. The opening to the sea allowed the drying, draining, burning and conversion of fringing wetlands into pasture. These changes began a phase of increased fine sediment and nutrient loading to the lake, causing eutrophication and increasing turbidity as well as reducing the suitability of the sediment for macrophytes. By the 1970s, the lake had become a eutrophic brackish lake with a much reduced water depth. Macrophytes were more or less disappearing from the lake by the 1980s and 1990s, resulting in the lake becoming the turbid, shallow, brackish, hypertrophic system that we are familiar with today.

8. The past 160 years of European settlement and development have resulted in substantial changes to Wainono Lagoon and the low-lying areas around it. The average sedimentation rate during the European era has been around 3 mm/y, similar to the rate calculated for lake Forsyth (Canterbury) and around half that calculated for Lake Waihola (South Otago). The shift in biotic communities from freshwater to brackish, the loss of macrophytes, and the substantial reduction in the extent of the lake-wetland complex have reduced many of the ecological values and ecosystem services once provided by the Wainono lake-wetland complex. However, the recent observation of *Ruppia*-type seagrasses growing in the lake

indicates that restoration could be possible, at least to the clearwater, brackish state that the lake was in between 1910 and the 1960s/70s.

Palaeo-limnological techniques are useful for determining environmental histories of coastal systems such as Wainono Lagoon. The use of such techniques in a number of similar systems to date indicates that similar patterns of degradation probably occurred in most east coast coastal lakes and lagoons in response to European settlement and the development of the landscape for agricultural production.

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1 Purpose of this study

Wainono Lagoon is a coastal lake located in South Canterbury. Much of its catchment is currently developed for intensive agriculture. The current water quality and hydrology of the lake is affected by landuse change, abstraction of water from the inflows for irrigation, and by lake water level regulation by artificial connection to the sea. Under the Canterbury Water Management Strategy (CWMS), the Lower Waitaki Zone Committee has prepared a zone implementation plan (ZIP) that recommends achieving outcomes for water quality and ecology within the south coastal Canterbury area. In the ZIP, improved ecosystem health is a primary objective for Wainono Lagoon. Key pathways for improving ecosystem health in the lake include a central and regionally funded restoration programme that aims to optimise lake level management, reduce sediment and nutrient loads, and rehabilitate fringing wetlands, as well as riparian planting and augmentation of lake inflows.

The current study was undertaken to determine the historical changes that Wainono Lagoon has undergone since European settlement and development of the area. Historical information on lake condition may be useful in underpinning the management and restoration plans for Wainono Lagoon and its catchment.

2 Background

Temperate coastal lagoons are a common landscape feature along the eastern and southern coasts of the South Island of New Zealand. These systems, which are dominated by fluvial (as opposed to marine) processes, have been classified into two distinct types by Kirk & Lauder (2000): the so-called “river-mouth lagoons” or *hapua* (the Māori term), and the coastal lakes, for which they propose the term “Waituna-type lagoon”. The latter type is defined as a typically fresh to brackish shallow body of water, more usually closed from the sea by a barrier bar than open to it. Waituna-type lagoons generally form on inter fan depressions – low-lying areas between coastal outwash fans. These types of systems form when the combination of climatic and hydrological conditions of the catchment and the supply of marine substrates by offshore or longshore currents combine to produce coastal fresh-brackish water bodies which are generally protected from the sea by gravel/sand bars. Many of these coastal systems, including their surrounding wetlands, provide habitat for flora and fauna and are important conservation areas. They provide additional valuable ecosystem services such as floodwater retention, seawater exclusion, sediment and nutrient retention, nutrient processing, habitat for valued wildlife and recreation opportunities such as hunting and fishing. In addition, Māori greatly value these systems because of their biological productivity, particularly with respect to mahinga kai species such as eels/tuna, lampreys/kanakana, waterfowl, and flounders/pātiki.

THE IMPORTANCE OF AQUATIC PLANTS (MACROPHYTES) IN SHALLOW LAKES AND LAGOONS:

In shallow lakes, enough light can penetrate the water column to allow macrophytes to grow throughout the depth range of the lake. Aquatic plants confer many ecological benefits. For example, they absorb plant nutrients such as nitrogen and phosphorus from the water and lake bed, thereby reducing available nutrients which could otherwise fuel nuisance phytoplankton blooms. Macrophytes, reduce currents and waves, reducing the stirring up of bottom sediments into the water column. This results in improved water clarity. Macrophytes also provide important habitat for invertebrates, zooplankton and fish, allowing for more diverse and productive aquatic food webs. Macrophytes also provide food for waterfowl, attracting ducks, geese and swans to lakes. In brackish, coastal lakes, salinity variations can be high and such conditions favour native seagrasses such as *Ruppia* sp., but also other salinity-tolerant plants such as native charophytes.

The presence of macrophytes in shallow lakes is a key indicator of the health of lakes because they encourage the presence of plentiful mahinga kai resources as well as a range of important ecosystems services. Because of their important roles in absorbing nutrients and suppressing sediment resuspension, they improve the resilience of lakes against the effects of human pressures such as nutrient and sediment loading as well as to alterations of the hydrological regime. However, these pressures, if too great, will eventually kill off macrophytes and this loss can be rapid, as in the case of Lake Ellesmere/Te Waihora (Gerbeaux 1993). With the loss of macrophytes comes the loss of the important ecosystem services they provide, resulting in lakes that have nuisance algal blooms, poor water clarity, low biodiversity, poor fisheries, and poor waterfowl populations. Under these degraded conditions (i.e., with algal blooms and high concentrations of resuspended sediments), it is very unlikely that macrophytes will re-establish. The successful restoration of macrophytes into a degraded lake is usually a very onerous and expensive undertaking. Much of the information presented here is detailed in Scheffer (2004).

Waituna-type lagoons are also known as intermittently closed and open lakes/lagoons (ICOLLs). ICOLLs are distributed along many parts of the New Zealand coastline including the south (e.g. Lake Onoke, Wairarapa) and east (Whakaki Lagoon, Hawkes Bay) coasts of the North Island/Te Ika o Maui and the west coast of the South Island/Te Wai Pounamu (e.g. Five Mile Lagoon, Westland). However, it is on the south and east coasts of the South Island/Te Wai Pounamu, where numerous Waituna-type lagoons occur, that these ICOLLs have been most studied.

Studies of coastal lakes and Waituna-type lagoons on the east coast of the South Island/Te Wai Pounamu reveal that these systems have been very dynamic over time, responding to sea level variation as well as anthropogenic activities such as land clearance, hydrological modification and agricultural activities (Schallenberg *et al.,* 2012). For example, Lake Waihola, a shallow tidal lake in South Otago, was part of a large estuary c. 4000 years ago, during the mid-Holocene sea level highstand (Schallenberg *et al,.* 2012). Since European arrival, around 85% percent of the lake-wetland complex that the lake had been associated with has been drained and converted to agriculture. Associated with the agricultural activity, increases in the rate of soil and riverine erosion have resulted in a c. 30-fold increase in the sediment infilling rate of the lake (Schallenberg *et al.,* 2012) compared to pre-European times. This pattern of increased sediment infilling associated with human activities in the catchment has been commonly reported for estuaries, coastal lakes and ICOLLs around New Zealand (Cosgrove, 2011).

Waituna Lagoon in Southland is an intermittently closed and open barrier bar lake/lagoon (ICOLL). The catchment of the Waituna Lagoon lake-wetland system has been subject to extensive conversion to intensive agriculture, associated with frequent burning, vegetation clearance, land drainage and conversion to dairying (Cosgrove, 2011). While this system is considered meso-eutrophic, it still maintains seagrass beds. The seagrasses have been fluctuating wildly in abundance in recent years and blooms of macroalga and phytoplankton threaten the ecological condition and ecosystem services of this system (Robertson *et al*., 2011). As occurs in many ICOLLs, water levels in Waituna Lagoon have been artificially lowered for decades by mechanically opening the barrier bar to allow the drainage of wetlands and the encroachment of agriculture to the lake shore. This hydrological management regime has substantially altered the ecological resilience and functioning of the lake ecosystem by changing the nature and duration of connections to the sea, the influence of seawater and sand on the lake, and the flushing of terrestrial materials from the lake (Schallenberg *et al.,* 2010). At the same time, terrestrial sediment and nutrient inputs to the lake will have reflected the onset and intensification of agriculture in the catchment. Nowadays, the higher nutrient and sediment status of the lake necessitates more frequent openings to allow more flushing of the lake. However, while flushing with seawater imparts a certain resilience to the effects of nutrient and sediment loading, the increasing influence of salinity may be altering the biological structure and functioning of the lake (Waituna LTG, in press).

Lake Ellesmere/Te Waihora is a large, classic Waituna-type lagoon in mid-Canterbury. Unlike Waituna Lagoon, Lake Ellesmere/Te Waihora is in a severely degraded state (hypertrophic), having lost its seagrass and macrophyte beds in 1968. The lake is subject to very high inorganic suspended sediment concentrations, turbidity and phytoplankton biomass with subsequent very low light penetration (Schallenberg *et al.* 2010). While the lake maintains a commercial eel/tuna fishery, it is generally considered to be degraded and attempts are underway to restore macrophytes to the lake. Since the early 1900s, Lake Ellesmere/Te Waihora has had its water level reduced artificially by mechanical breaching of the barrier bar. As in the catchment of Waituna Lagoon, this water level regulation has allowed the drainage of fringing wetlands and the encroachment of agriculture to the lakeshore. While the prevalence of loess soils in the catchment probably contributed some turbidity to the lake in pre-European times, land use conversion to agriculture has contributed to sediment and nutrient loading and to a progressive reduction in water quality to the point at which macrophytes have been unable to re-establish in the lake. The lake is so large that flushing and mixing with sea water during lake openings is much less efficient than in Waituna Lagoon (Schallenberg *et al.,* 2010). Therefore the fluctuations in salinity and nutrient levels tend to be more dampened over time in Lake Ellesmere/Te Waihora than in Waituna Lagoon (Schallenberg *et al.,* 2010).

Lake Forsyth/Wairewa is a smaller ICOLL situated on the Banks Peninsula, near to Lake Ellesmere/Te Waihora. Prior to the mid-1800s, the lake was an open estuarine inlet, but a barrier bar naturally formed across its mouth soon after the arrival of European settlers. The catchment of Lake Forsyth/Wairewa is relatively small and very steep and is underlain by basaltic geology, which is relatively rich in phosphorus. Thus, phosphorus levels in the lake were probably naturally relatively high. Parts of the Lake Forsyth/Wairewa catchment were converted to dairy farming in the early 1900s and this, coupled with episodic closure to the sea, resulted in early algal blooms. Water level management by mechanical breaching of the barrier bar has also occurred in Lake Forsyth/Wairewa and sediment core analyses indicate that this practice has increased the mean salinity of the lake (Reid *et al.,* 2004; Woodward & Shulmeister, 2005). In recent times, this lake has been alternating between macrophyte-dominated and phytoplankton-dominated states. In the latter phase, toxic blooms of the cyanobacterium, *Nodularia spumigena*, have occurred on numerous occasions. Characterization of sedimentary diatoms also indicates that since European colonisation of the area, the lake has become more nutrient enriched, progressing from an early mesotrophic state to a hypertrophic state in recent years (Woodward *et al.,* 2005). Moreover, the rate of sediment infilling has increased from around 1 mm/y to around 3 mm/y.

These studies highlight the temporal dynamism of coastal lake ecosystems and their vulnerability to environmental change. The ecological vulnerability and resilience of shallow lakes to environmental pressures relates directly to ecological thresholds or tipping points and ecological feedbacks in these complex ecosystems (Scheffer, 2004). Attempts to manage, and especially to restore such systems from a degraded state require good understanding of their ecological dynamics as well as baseline conditions and the historical trajectories that these systems have traveled in response to anthropogenic pressures that have been exerted upon them.

3 Wainono Lagoon

Wainono Lagoon (44.7° S, 171.15° W) is located on the eastern coast of the South Island of New Zealand in the South Canterbury region, district of Waimate (Figure 4-1). At its normal water level of 1 m a.s.l. the lake has a surface area of around 325 ha. At 1.5 m a.s.l., its surface area is around 420 ha. It is separated from the Pacific Ocean by a narrow gravel barrier or berm. Several streams feed the lake, notably the Hook River in the North. The outflow of the lake is to the south via "The Dead Arm", which is a 7 km reach of river that breaches the coastal gravel bar at the Waihao Box. The hydrology of the lake is complex and when the discharge location to the sea is blocked, the Waihao River may back up into Wainono Lagoon.

The outlet to the sea across the gravel barrier is remote from the lake itself. Generally seepage from the lagoon across the barrier bar is sufficient to allow the water load from the catchment to discharge. So to minimise the lagoon's water level for agricultural purposes, a device was built in 1898 to try to maintain a permanent opening. This device was damaged in a subsequent storm and then the Waihao Box was built in 1910, which is still in operation today. The box is designed to discharge normal flows, not flood flows. However, when flows in the Waihao River are less than 6 m^3/s, longshore drift of gravel ensures that the box remains closed or has only short openings. Todd (1988) reported that the box had remained closed by longshore drift of gravel for around 75% of the time, requiring mechanical opening by bulldozer when the need arose.

Wainono Lagoon is presently a freshwater-brackish lake. Sea water either enters by seepage through the barrier bar, or more substantially, by the sea overtopping the barrier bar during periods of large swells and storm surges when associated with high tides (Environment Canterbury, 2004). Overtopping can breach the barrier allowing substantial amounts of sea water to ingress, sometimes flooding farmland. Benn (1988) reported that historical overtopping and breaching of the barrier bar had flooded the whole of the lagoon and large areas of land around the lagoon. Significant barrier breaches occur every 3-5 years (Environment Canterbury, 2004). In recent decades, the breach and associated flooding that occurred in July 1985 was considered to be severe (Kirk, 1987). Hicks and Todd (2003) considered that, despite the barrier undergoing continual erosion for at least decades if not longer, the barrier beach volume had probably remained stable for thousands of years. Undoubtedly, Wainono Lagoon has been affected by hydrological modification and land use change, but Hart *et al.* (2008) stated that substantial infilling would also have been caused by coastal erosion and beach roll-over processes.

The salinity of the lake water was highly variable between June 2009 and May 2011, ranging between 5% and 25% of seawater salinity (Sutherland & Norton, 2011) or 1.7 ppt and 8.5 ppt. Although generally not tidal, the lake has been reported to be tidal for several days to several weeks when open to the sea (Pierce, 1980). Local long-term residents reported that the lake had been deeper and clearer in the past (Benn, 2011) and in 1976, McLay (1976) described the lake as "clean" and similar to its condition in 1965. In contrast, the lake has recently become hypertrophic, which means that it has high algal biomass and nutrient concentrations. The phytoplankton of the lake during the hypertrophic phase has typically included diatoms, dinoflagellates, green algae and cyanobacteria, although there had been no reports of cyanobacterial blooms in the lake up to 2011 (Sutherland & Norton, 2011). The bottom sediments of the lake consist of easily suspended fine muds (Pierce, 1980) and this, together with the lake's shallowness and exposure to prevailing winds, results in episodes of severe wind-induced sediment resuspension (Sutherland & Norton, 2011). Therefore, it is not surprising that macrophytes were reported as absent from the lake in 2003 and 2011 (Sutherland & Norton, 2011). However, small *Ruppia*-like plants were observed growing near the middle of the lagoon and were washed up on the shore in the summer of 2012/13 (M. Schallenberg, pers. obs). Previously, submerged macrophytes including *Myriophyllum triphyllum*, *Ruppia megacarpa*, *Lilaeopsis novazelandia*, *Potamogeton crispus* and *Ranunculus* sp. have been recorded in the lake (Pierce 1980; Sutherland & Norton, 2011). In addition Wood & Mason (1977) found the charophytes, *Nitella hookeri* and *Nitella pseudoflabellata,* from the lower Waihao River.

Little is known about the invertebrate community in the lake but Pierce (1980) reported that the muddy substrate and high salinity variations at irregular intervals were responsible for the depauperate invertebrate fauna, which included primarily chironomids, tipulids and amphipods, with the presence of some oligochaetes, snails (*Potamopyrgus* sp.), sand-encased caddis fly larvae (*Pycnocentri*a sp.) and the larva of the aquatic moth, *Nymphula nifens*. In addition, the mysid shrimp, *Tenagomysis novazelandiae* and water boatmen were common in the less saline areas.

The main ecological values recognised in Wainono Lagoon are the fish and bird communities which use the lake habitats. Fish species using the lake include eels/tuna, lampreys/kanakana, flounder/pātiki, smelt and inanga (see Benn, 2011 for more information). Wainono Lagoon is internationally recognised as a habitat for birds including waterfowl, which are important as mahinga kai as well as to recreational hunters who use the lake (see Benn, 2011 for more information).

Given the current state of the lake and the historical information highlighting major changes in the lake and its catchment over the past 150 years, we hypothesised that Wainono Lagoon has experienced significant anthropogenically-induced changes since the arrival of European settlers in the region in the mid-1850s. We used the palaeolimnological approach to acquire information about the historical environmental condition of the lake and to infer the lake's responses to anthropogenic pressures over the past 150 years. Our objectives were to establish baseline conditions for Wainono Lagoon and to evaluate the degree of human-induced change that this system has experienced over the last 150 years.

4 Methods

The lake was cored on 14 October 2012, using a 80 mm diameter tube that was pushed into the bottom sediments first by hand and further by using a sledgehammer. The coring site was selected to be in the deepest zone of the lake and well away from potential high episodic sediment depositional and erosional areas (Fig. 4-1). Thus, we hoped to maximise the chance of obtaining a continuous and historically long sediment chronology. Two cores were retrieved in this way. Core A measured 61 cm and core B 86 cm. We used core A for most of our analyses (except macrofossil identification) because the uppermost few centimetres of core B were disturbed during transport to University of Otago. The cores were subsampled in the laboratory at 0.5-1 cm intervals. Lake conditions on the day of sampling are provided in Table 4-1.

We determined the chronology of core A through radiometric analysis. Total activities of ^{210}Pb and ^{137}Cs were measured on 15 lyophilized samples in a gamma-ray spectrometer. Analyses were conducted at the School of Geography, Environment and Earth Sciences, Victoria University of Wellington (by Dr. Uwe Rieser).

We measured moisture and organic carbon content of the sediments at 0.5 cm intervals in core A (entire core), and at 1 cm intervals in core B (from 36 to 86 cm depth) using the method outlined in Heiri *et al.* (2001). Briefly, 1g samples (± 0.01g) of wet sediment were weighed and dried in a muffle furnace at 100°C for 24h. Dry weight was measured and the samples were combusted at 600°C for 4 hours and left to cool before being weighed.

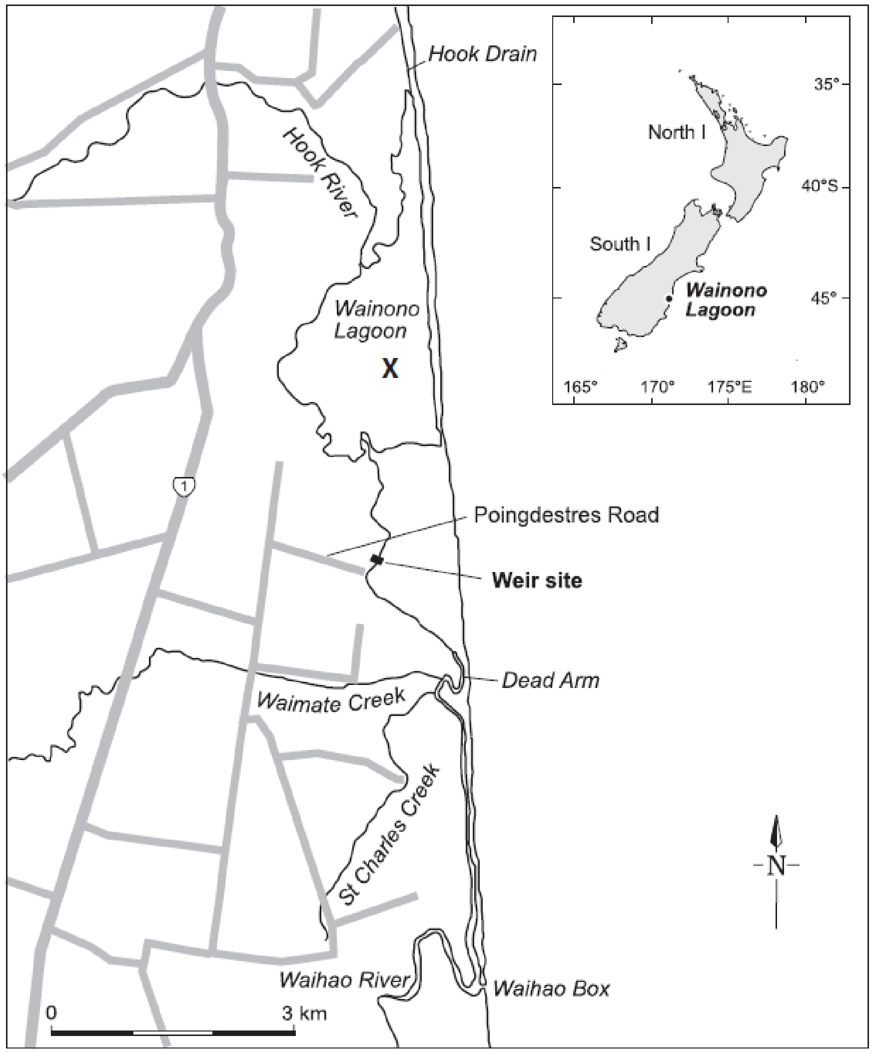


Figure 4-1: Wainono Lagoon location map with key features and sampling site indicated

Table 4-1: Conditions in Wainono Lagoon on day of coring (2012-10-14)

Latitude and longitude of coring site	-44.703009, 171.160383
Depth at coring site	1.1 m
Specific conductivity	297 µS (micro Siemens)
Salinity	0.16 ppm
Water temperature	10.8°C
pH	slightly alkaline (around 8)
Transparency	highly turbid

Magnetic susceptibility (MS), which provides a qualitative indication of sediment magnetic content, is also useful for identifying changes in the nature and provenance of sediment. MS was measured on discrete samples at 0.5 cm intervals using an MS2 Bartington meter (University of Otago Geology Department). Five measurements were made for each sample, and then averaged.

Grain-size analysis is a useful measure of the composition of the sediment and can also be used to identify changes in the nature and provenance of sediment. It was performed at 0.5 cm intervals following the method of Parris *et al.* (2009). Briefly, 300 mg of sediment was treated with 30% H_2O_2 for

3 days to remove organics. Then, 10 ml of 1M NaOH was added and left for 48 hours to remove biogenic silica (BSi). Finally, samples were centrifuged and re-suspended in a solution of sodium pyrophosphate (final concentration = 5% w/v). They were analysed using a Malvern 2000 Mastersizer (University of Otago Geography Department).

Twenty-one samples selected from core B were sieved through a 180 micron mesh using deionized water in order to evaluate presence/absence of aquatic and terrestrial macrofossils using a Zeiss stereomicroscope. De Winton *et al.* (2007) was used to help identify charophyte oospores.

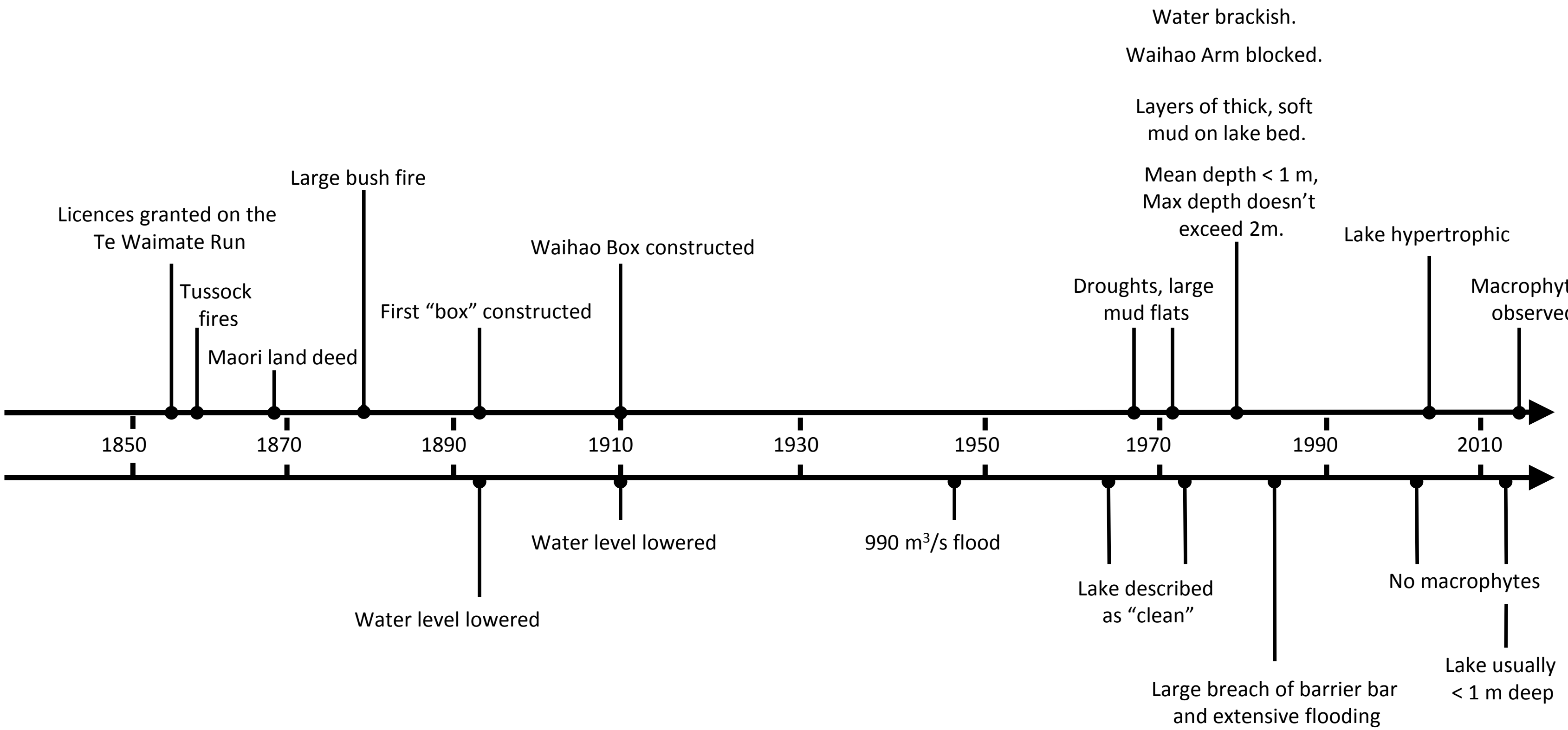
Diatom slurries were prepared for 25 samples from core A. The standard protocol using H_2O_2 was applied (described here: http://www.geog.ucl.ac.uk/about-the-department/support-services/laboratory/laboratory-methods/lake-sediment-analysis/diatom-preparation). Briefly, between 0.1 and 0.2 g of wet sediment was treated with 5 ml of 30% H_2O_2 and were left to digest for one week before being rinsed several times with distilled water. A few drops of the slurries were left to dry at room temperature on cover slips before being permanently mounted onto slides using Meltmount™, a thermal plastic with a refractive index similar to Naphrax (1.704). Diatoms were enumerated and identified under phase contrast at 100x magnification using a Leica Axiophot microscope. Identification of taxa relied mainly on Foged (1979), and on some northern hemisphere floras such as the Krammer-Lange-Bertalot series (2004-2008). Results of macrofossil and diatom analyses were plotted using the software C2 (Juggins, 2003). Zonation of the diatom record was established using cluster analysis in the software MVSP (Kovach, 2004) and the significant number of zones determined using the broken stick model (Bennett, 1996).

Historical sources of information about the Wainono Lagoon and its catchment were sought to obtain a historical time line of environmental change which we used to help interpret the palaeolimnological data (Table 4-2).

Table 4-2: Timeline of environmental change derived from historical accounts and previously published data sources. See Figure 4-2

Date	Condition of catchment	Condition of lake and hydrology	Reference
1844 AD	First European report that hundreds of Māori occupy Waimate and Wainono Lagoon areas. Thousands of acres of quaking swamp from Willowbridge to Makikihi R.		Studholme (1940)
1855-1859	Licenses totalling 98,500 acres granted on the Te Waimate run		www.Waimate.com
1859	Significant tussock fires reported in district		Buller (1898)
1868	Land deeds to Māori in Waimate area to enable continuation of food gathering lifestyle		Tipa & Associates (2012)
1878	Large bush fire in area of Waimate and Wainono Lagoon		Studholme (1940)
1890s	Wetlands drained and farmland encroaches on lake	Original “Box” constructed, but was destroyed.	Benn (2011)
1910	Wetlands drained and farmland encroaches on lake	Waihao Box constructed	Benn (2011)
1945		990 m3/s flood in Waihao R.	Cowie (1957)
1965		Lake described as “clean”	McLay (1976)
1969		Drought caused lake to become shallow (<0.6 m deep). Extensive mudflats exposed.	Pierce (1980)
1973		Drought caused lake to become shallow (<0.6 m deep). Extensive mudflats exposed.	Pierce (1980)
1976		Lake described as “clean”	McLay (1976)
1977		Blockage of Dead Arm – dredging.	Benn (2011)
1980		Water brackish, 5-25% seawater	Pierce (1980)
1980		Macrophytes reported	Pierce (1980)
1980		Waihao Arm needs dredging because eroding coastline blocks drainage southward	Pemberton (1980)
1980		20-40 cm-thick layer of soft mud easily stirred up by winds	Pierce (1980)
1980		Lagoon average depth < 1m, never exceeds 2 m	Pierce (1980)
1985		Large breach of barrier bar and extensive flooding	Kirk (1987), Todd (1988)
2003		Macrophytes absent	Sutherland & Norton (2011)
2004		Lake hypertrophic	Sutherland & Norton (2011)
2011		Macrophytes absent	Sutherland & Norton (2011)
2011		Lake usually < 1 m deep	Sutherland & Norton (2011)
2012		Macrophytes reported	M. Schallenberg (pers. obs.)

Figure 4-2: Timeline of environmental change derived from historical accounts and previously published data sources. See Table 2 for sources



5 Results and discussion

5.1 Core chronology and sediment properties

The chronology of the sediment core (Figure 5-1) is anchored at 14.25 cm depth with the peak in ^{137}Cs activity indicating the year 1963 (±2 years). ^{210}Pb, which has its source in the lower troposphere over continents, is only present in low concentrations in oceanic regions of the southern hemisphere, making ^{210}Pb-based dating challenging in New Zealand lake sediments. Below 27.5 cm in the Wainono core, there are uncertainties in calculating excess ^{210}Pb. However, taking the 51.1 Bq/kg value of the sample at 0.75 cm depth as a baseline for the modern surface concentration, a sedimentation rate of approximately 6.5 cm per ^{210}Pb-halflife (22.3yr), or ca. 0.3 cm/year can be calculated. Assuming a constant sedimentation rate, core A would cover approximately a 200-year period, from 1812-2012.

The sediment in core A had a high water content, averaging 44% of fresh weight, but showing a distinct period of higher-than-average values at the bottom of the core (Figure 5-2), followed by decreasing values and a stable period, with a further decreasing trend and finally a very recent small increase in the core top. Using the OM content, we wiggle-matched core B (which wasn't dated) to core A. The bottom of core A (61 cm depth) corresponds roughly to 75 cm depth in core B. This allowed us to estimate the ages at various depths in core B.

The organic carbon content of lake sediments is a function of aquatic and terrestrial productivity, and sediment influx from the catchment. In core A, the average organic matter content (OM) inferred by loss-on-ignition is quite low (around 4% per gram dry mass). If OM supply rates were constant, then one would expect OM content to decline with depth in the core because of progressive decomposition over time. We observe the opposite pattern in Wainono Lagoon, where OM content was higher at depth than at the top of the core (Fig. 5-2). This suggests that there were substantial changes in type and quantity of OM sedimenting in the lake over time, with higher organic matter inputs in the past than in recent times. There are few significant variations in OM throughout the core. For example there is a sharp rise in the 1820s to 1830s. There is also a distinct decreasing trend in the upper section of the core, from the early 1970s to the present.

The inorganic fraction of the sediment is mainly composed of silt (2 to 63 μm in diameter), clay (< 2 μm diameter) and sand particles (> 63 μm diameter) (Fig. 5-2). Silt is the dominant fraction, making up an average of 80% of the sediment throughout the core, followed by clay (14%) and sand (6%). The dominance of silt and clay, which are very small particles that are easily suspended in the water column, is consistent with the high turbidity in the lagoon. However, near the bottom of the core at around 1850, the sand content increased abruptly to around five times the mean core sand content. If our chronology is correct, this would correspond remarkably well to the time of the first major land clearance episode at the time of European settlement in 1855-1878 (Fig. 4-2 and Table 4-2). Large-scale land clearance is usually accompanied by high soil erosion rates and increased flood risk, which is consistent with an elevated sand content.

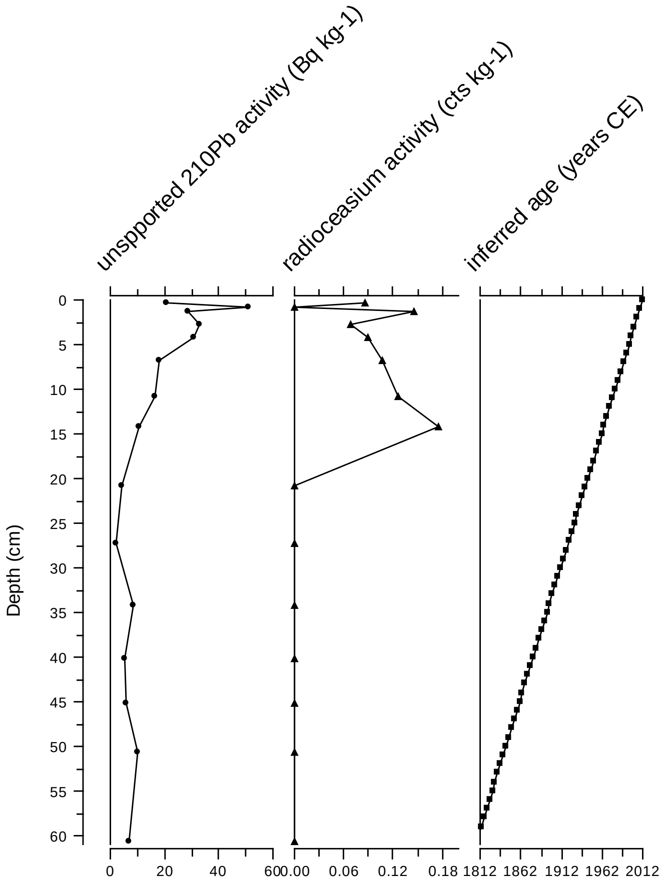


Figure 5-1: Core chronology and sedimentation rate inferred by ^{210}Pb and ^{137}Cs dating. The peak in radiocaesium corresponds to 1962-1965, when nuclear fallout was at its highest. The errors on the inferred dates increase with depth and the dating limit of ^{210}Pb is around 150 years before present. Here, we indicate a constant sedimentation rate throughout the core. However, based on the results of the analyses of the biotic indicators in the core, we believe that there is a discrepancy in this trend towards the bottom section of the core, with the depths around 55 cm corresponding to the arrival of Europeans in the region (see Fig. 5-2)

5.2 Diatoms

We identified 65 species of diatoms in the sediments of core A. Dominant species (at least 5% relative abundance in at least one sample) are presented in Figure 5-2.

The three zones identified in the core are based on the changes in the diatom assemblages, which correspond well with the changes in the sediment properties (Fig. 5-2). In Zone 1, diatoms were rare or absent. Only a few frustule fragments were found between 54 and 61 cm depth. We also investigated samples from the longer core B, in order to verify if diatoms were present at deeper depths. After verification using x-ray, it was determined that only the top few centimetres of core B had been disturbed during transport, justifying the use of the lower section of this core for macofossil analysis. Since we estimated the bottom of core A to correspond to about 75 cm depth in core B (based on OM content), we looked at samples above and below this depth to confirm the match-up between the two cores and also to find out if diatoms reappeared further down in core B. Based on presence/absence of diatoms, we confirmed the match between the bottom of core A with 75 cm depth in core B. Diatoms were absent or very rare throughout the bottom section of core B (75-86 cm).

In core A, zone 2a starts at around 52-53 cm depth (early 19th century) and sees the appearance and establishment of a diatom assemblage dominated by small *Fragilaria sensu lato*. The most abundant taxa in this zone are *Staurosirella pinnata* complex, *Pseudostaurosira brevistriata* complex, *Staurosira construens* and *Staurosira construens* var. *venter*, in decreasing order of abundance. This freshwater group includes taxa that are tolerant of strong mixing, suggesting that Wainono Lagoon has been a well-mixed shallow water body throughout the time period represented by this core. Despite this turbulent environment, the ^{210}Pb dating suggests that the deposition of the sediments is not significantly disturbed by the mixing in the water column. The absence of coastal taxa in this deeper part of the core suggests little connection to the sea during this period. The *Staurosirella pinnata* and *Pseudostaurosira brevistriata* complexes are made up of epipsammic taxa, which means that they often occur attached to sand grains. Their marked presence in this zone is concurrent with the high sand content of the sediment at that time.

The beginning of Zone 2b is marked by a decrease in the sand content, the MS and the moisture content. The diatom assemblage is overwhelmingly dominated by the *Staurosirella pinnata* complex in this zone (often >50%).

In Zone 2c, a notable change in the assemblage occurs with the appearance of *Hyalodiscus scoticus* and *Planothidium* cf. *lanceolatum*. A change in the lithology was also noted at this depth in the core, with a transition from black-brownish to black-grey clayey sediment. Reports on the autecology of *H. scoticus* in the literature are somewhat confusing. It has been described as both a common epiphyte (of either seaweed or of other diatoms) in shallow coastal North Pacific regions (Valdivostok by Skvortsow (1932); Japan by Takano (1962)) and also as a coastal planktonic-tychoplanktonic species (Baltic Sea by Risberg (2002)). Notwithstanding this confusion about its life-form, it appears that this is a coastal species found at relatively shallow depths and that it is tolerant of large fluctuations in salinity. *P. lanceolatum* is described as rheophilic (i.e. prefers to live in fast-moving water) and is indifferent to salinity. It has been documented as a common species in hot springs of the Sakhalin Islands (Far-eastern Russia), found alongside many marine and brackish species (Nikulina & Kociolek, 2011), as well as in rivers of eastern North America (Lavoie *et al.* 2008). The appearance of these two taxa in the lagoon a short time after the installation of the Waihao Box is consistent with enhanced inflow of sea-water into the lagoon, as would be expected after the creation of an artificial connection to the sea. The Waihao Box is likely to have increased the amount and variability of the salinity in the lagoon.

Support for this theory, as opposed to an increase in salinity being caused by changes in extreme climate events, can be found in eyewitness reports from the 1980s. In 1985, the Canterbury coast in the Wainono region received three severe storms, in April, May and July. This resulted in a weakening of the barrier separating the lagoon from the ocean during the first two storms, followed by a breach of the ridge during the third storm (Table 4-2). The combined effects of these events resulted in a 1.6 m lowering of a 1.2 km stretch of the sand and gravel beach ridge barrier as well as 80 ha of land in the Wainono catchment being inundated by sea water. Based on our analysis of the lagoon sediments, there is no indication that these storms had a marked impact on the ecology of the lake.

The *Fragilaria sensu lato* continue to dominate the assemblage following the appearance of the coastal species, however, there is an abrupt switch in the dominance from the *Staurosirella pinnata* complex to *Staurosira construens* var. *venter* (Zone 3), indicating that this taxon is more tolerant of variable salinity.

At the top of the core, *Navicula gregaria* and *Nitzschia palea* appear, two taxa that are considered tolerant of organic pollution (Kelly & Whitton, 1995). These taxa become more abundant in the surface sediments, indicating that the lagoon started to become more eutrophic around the early 1980s.

Additionally, the very recent appearance of the taxon *Stephanodiscus hantzschii* in the top of the sediment core is not surprising because this small centric diatom is indicative of anthropogenic eutrophication and is associated with increased levels of nitrogen and phosphorous (see refs in Jung *et al*., 2009). Blooms of *S. hantzschii* are considered problematic as they contribute to lower water transparency and confer an unpleasant odour and taste on the water.

The absence of diatoms in Zone 1 of the cores is puzzling because the macrofossil analysis, which revealed remnants of aquatic animals and plants at these depths, suggests the presence of freshwater. There are several possible explanations that can be put forward in order to explain the absence of diatoms. For example, in the context of a high-flow regime, diatom communities can be disrupted (Van de Koppel *et al.,* 2001). In semi-permanently closed systems with little nutrient input, diatom communities can be inhibited by the restricted availability of new nutrients and/or silica (Perissinotto *et al.,* 2000). In shallow, turbid waters, with low sediment accumulation rates and no macrophyte beds, diatom valves have a tendency to become highly fragmented (Flower, 1993). In a marsh environment, shallow, fluctuating water levels can account for limited open water and diagenic removal of aquatic fossil components. Finally, during an episode of intense and prolonged desiccation, diatom frustules deposited on the surface of the lake bed can be blown away by the wind, leaving a hiatus in the sedimentary sequence (Reed, 1998).

The description of the pre-European landscape of the low-lying area between Willowbridge and the Makikihi River as that of a “large quaking swamp” (Studholme, 1940) gives insight as to why diatoms might not have been preserved in the pre-European Wainono lake-wetland complex. Such a system may not have had much open water or the water may have been low in nutrients, including silicon. In addition, quaking swamps and bogs have significant peat production which can reduce the pH of the water (e.g. M. Schallenberg has measured a pH of 4.6 for a peat-surrounded lake (Lake Wilkie in the Catlins)). Diatom frustules dissolve in low pH waters (Flower, 1993). Thus, we believe, based on the diatom reconstruction, that the sediments in Zone 1 reflect those of Wainono Lagoon when it was part of an extensive coastal swamp-wetland system with substantial peat production, in which either low Si content and/or low pH inhibited diatom preservation in the sediments.

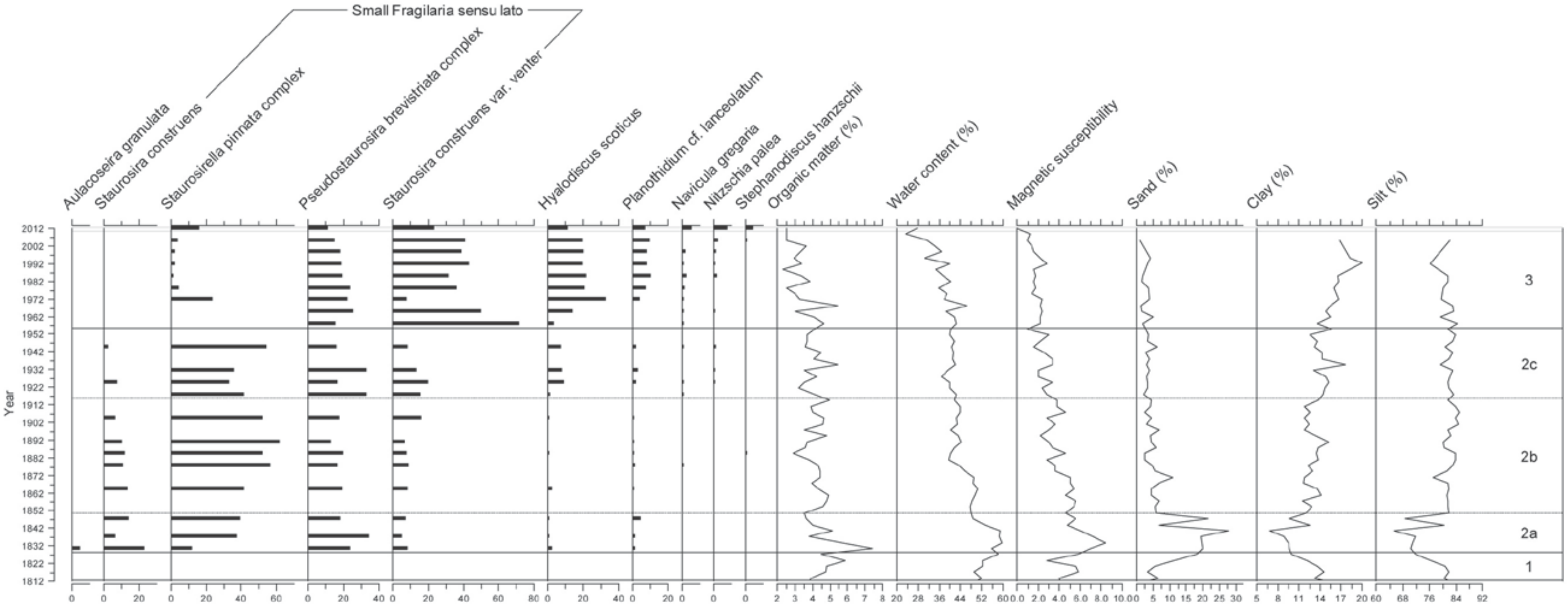


Figure 5-2: **Stratigraphic succession of sedimentary diatom assemblages and some physical characteristics of the Wainono Lagoon core A. *Hyalodiscus scoticus* is a coastal diatom. The others are either freshwater taxa or are indifferent to salinity. The ages of the transitions between Zones 1 and 2a and 2a and 2b were derived from ^{210}Pb dating and are thus subject to some uncertainty. The distinct changes observed in the sedimentary indicators near the bottom of the core are believed to correspond to the arrival of Europeans in the region in c. 1850 and to c. 1880, respectively (see Fig. 5-1 for explanation)**

5.3 Macrofossils

The analysis of macrofossil data from core B supports the interpretation of historical environmental change deduced from the diatom analysis and adds detail as to the make-up of the biotic assemblage in the lagoon over the past >150 years. The sediment of core B below 58 cm was characterised by the absence of sand and the dominance of fine silt and clays. There were few macrofossils, but the ones that were observed indicated a freshwater environment. Thus, the zone below 58 cm in Core B corresponded with Zone 1 in Core A, the zone of the diatom hiatus. This was supported by examination of diatoms in these strata of Core B, which were very sparse.

Moving up from 58 cm in Core B, the samples contained much sand, woody organic matter, freshwater sponges, charophyte oosproes from the genera *Chara* and *Nitella*, and *Daphnia* ephippia (resting eggs). The native zooplankter, *Daphnia carinata,* is an excellent indicator of freshwater conditions as it has a very low tolerance for salinity (Schallenberg *et al.,* 2003). The rest of these biotic indicators are all consistent with conditions reflecting a relatively clear freshwater, or mildly brackish, lake. This assemblage showed up consistently in samples up to 28 cm and this corresponds well with the freshwater diatom assemblage found in Zone 2 of Core A. Zones 2a and 2b were distinguished by the high sand content in the older 2a strata and this was also observed under microscopic examination of Core B, in which sand was abundant from 58 cm to 48 cm. Along with lower sand content, Zone 2b in Core B (42 to 28 cm) contained numerous charcoal particles, which were absent in Zone 2a.

In the strata between 28 and 8 cm in Core B, a transition to brackish water was inferred by the disappearance of *Daphnia* ephippia, carophyte oospores and sponges. Organic detritus in these strata was characterised as fibrous and may reflect the presence of the seagrass, *Ruppia* sp., in the lake. One *Ruppia* seed was also found in this transition zone, which corresponds with Zone 2c in Core A and which was characterised by the introduction of a halotolerant diatom species (*Hyalodiscus scoticus*).

Zone 3 in Core A was between 15 cm and the top of the core. Diatom taxa reflected brackish conditions and eutrophication. The macrofossils from the strata between 8 cm and the top of Core B also reflected conditions indicative of productive brackish lakes with an abundance of chironomid head capsules and caddis fly cases and a lack of macrophyte propagules and detritus. Charcoal and sand were also evident in the samples from the top of the core suggesting continued land disturbance and possibly increased marine influence.

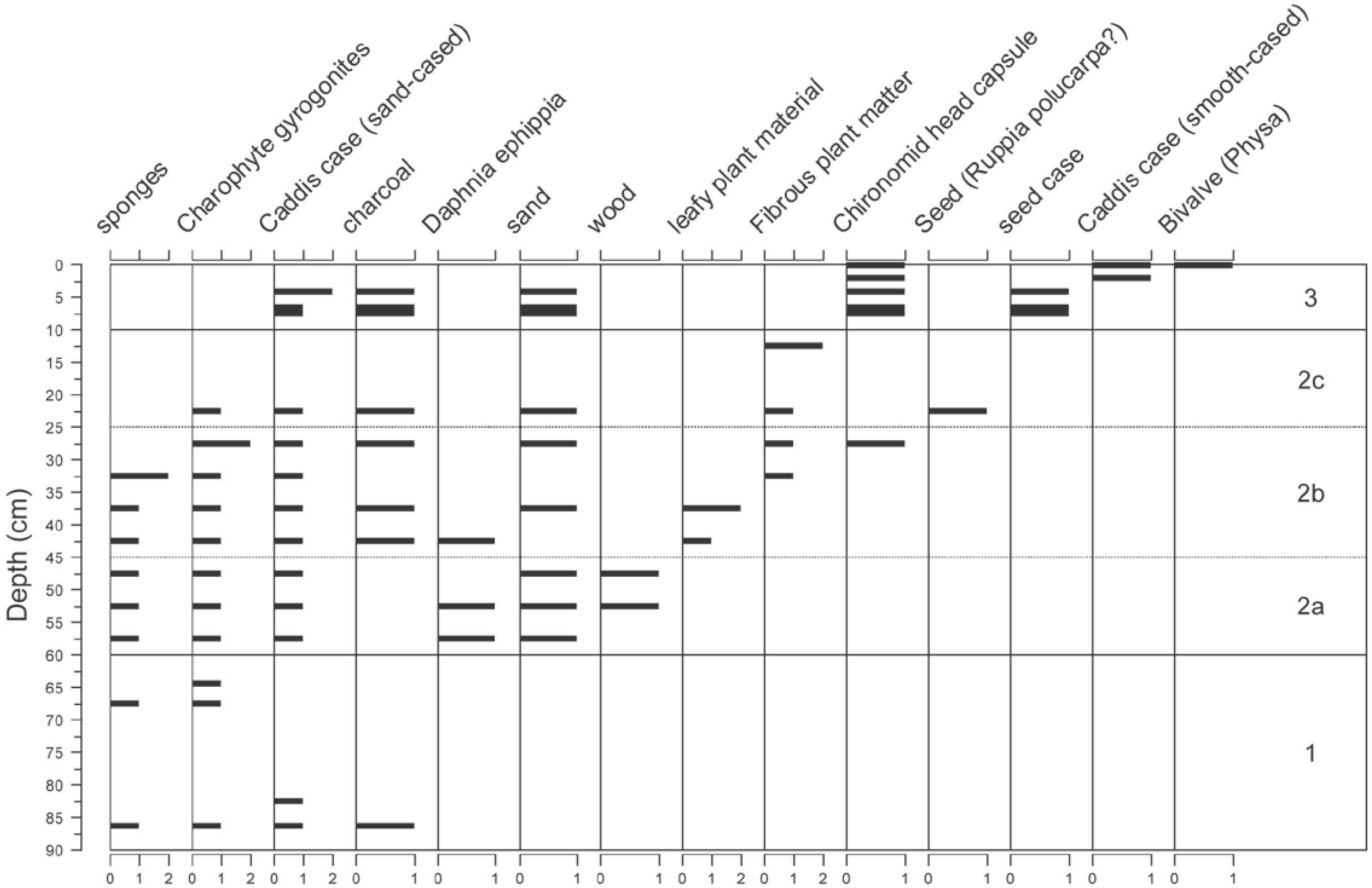


Figure 5-3: **Stratigraphic succession of macrofossils from the Wainono Lagoon core B. Bars indicate presence (Short bars "1" indicate present in low to moderate abundance, long bars "2" indicate present in higher abundance). The y-axis is depth below the surface of the lake bed in cm**

6 Inferred environmental history

Waituna-type lagoons such as Wainono are not static, unchanging features of the landscape (Kirk & Lauder, 2000), but are dynamic systems which are affected by sea level, climate and land use. Compositional characteristics and the biotic content of sediments from Wainono Lagoon revealed that this system has been significantly impacted by local anthropogenic activities since European settlement in the mid-19th century. Firstly, a relatively thick stratum with a high content of sand-sized particles (> 63 μm) was observed at a depth in the core which corresponds to the mid-19th century. Large fires were recorded in the catchment around Waimate in 1859 and 1878 (Table 4-2; Fig. 4-2). These fires would have prepared the ground for vegetation clearing and tillage, which would have resulted in large-scale erosion of the upper catchment. First, fine sediments (clays and silt) would have moved down the catchment, followed by coarser materials, which would have required less frequent, larger floods to deliver them to the lake-wetland complex. We have interpreted Zone 1 as the pre-erosion sediment of the lake prior to it being influenced by European land disturbance (Table 6-1). Alternatively, the material in Zone 1 might represent the early erosional phase of fine sediments after the initial upland land clearance activities of mid-1800s (Table 4-2). The presence of rare charophyte oospores, sponges and caddisfly cases indicates that at this time, the lake was in a predominantly freshwater phase, with relatively clear water. An early European impression of the landscape in the Wainono Lagoon area describes it as an extensive quaking swampland (Table 4-2; Fig. 4-2). Such a "swamp" would have had a large peat component and it is likely to have been a wetland with a very low-nutrient status (i.e. oligotrophic or dystrophic), with high water colour due to dissolved humic substances and possibly with a low pH. Such conditions might not favour the preservation of diatom frustules in the lake sediment. However, the lack of diatoms in Zone 1 could alternatively have resulted if Zone 1 represented an erosional period, where materials produced in the lake would have been substantially diluted by incoming fine sediment, followed subsequently by coarser sediment particles (e.g. Zone 2a). At this time, the water level would have been higher than the present water level, and seepage to the sea would have been the main outflow pathway. Perhaps during large flood events, the water level might have risen enough to break out of the lake-wetland system into the ocean, opening up a temporary connection to the sea. Overtopping by waves during heavy seas and spring tides would probably have occurred, but the large lake volume at the time would have diluted such marine input much more than the dilution of seawater that occurs today when the gravel bar is overtopped. Today, with artificially lowered water levels resulting in a much smaller wetland system, marine inputs will have a greater effect on salinity variations in the lake. In addition, the sea level around New Zealand has risen c. 160 mm in the past century (Hannah, 2004) and this rise will increasingly facilitate overtopping of the gravel barrier bar during high seas unless the height of the barrier also rises.

With the arrival of European settlers in the 1850s, land was allocated to clearance and farming activities. Rapid devegetation by fire and subsequent tillage would have converted much of the upland coastal areas to farmland by the end of the 1870s (Table 4-2; Fig. 4-2). Erosion of coarse sediments into the lake explains Zone 2a, which shows highly elevated sand content (Fig. 5-1). During this phase, the wetland areas would have remained mostly intact, acting as a partial buffer against many direct effects of farming activities (e.g. stock ingress, eutrophication, erosion). Lake sediments from this era indicate that the lake was predominantly freshwater, containing charophyte macrophytes, freshwater sponges and *Daphnia* zooplankton. *Daphnia* is not tolerant of salt water (Schallenberg *et al.,* 2003) and the charophytes and sponges can only tolerate short periods of moderate salinity (e.g. 6 ppt) as these taxa are not found in consistently, or moderately, brackish systems (M. Schallenberg, pers. obs). The lack of charcoal in Zone 2a is surprising, but it may have been diluted by high rates of sand input from the catchment. As the sand content declined into Zone 2b, charcoal became abundant in the sediments. Apart from these changes, the sediment in Zone 2b contained similar macrofossils to that in Zone 2a, indicating that a relatively stable freshwater lake environment persisted during this time (Table 6-1).

A marked transition occurred in the lake sediments starting in the early 1900s. The transition was away from a charophyte-dominated freshwater lake to a brackish lake with *Ruppia* seagrasses present (Zone 2c). This transition coincided with the construction of the Waihao Box. The establishment of an artificial connection to the sea lowered the water level of the lake-wetland complex, allowing the encroachment of agriculture, which probably would have followed the burning of the dried out wetlands and tillage of the soils. This would have brought farming impacts into direct contact with the lake by removing the wetland buffer. Progressive conversion of land nearer to the lake and the opening up of drains in the vicinity of the lake would have released finer sediments into the inflows, gradually increasing the clay content of the lake sediments. Salinity levels would have risen markedly, as supported by the first appearance of the halophilic diatom, *H. scoticus* (Fig. 5-2) and as is indicated by the loss of *Daphnia*, charophytes and sponges (Table 6-1).

Zone 3 reflects the modern era of Wainono Lagoon, with progressive eutrophication, increasing turbidity, consistent brackishness, and loss of macrophytes (including *Ruppia*). The transition to this era seems to have begun in the 1960s or 1970s (Table 4-2; Fig. 4-2). Agriculture has intensified in recent decades, with more irrigation in the catchment, more drainage and more farming encroaching on the lake margins. During this period, benthic invertebrates in the lake have been dominated by chironomids and caddisfly larvae (Table 6-1) - a biological community similar to that in present-day Lake Ellesmere/Te Waihora (M. Schallenberg, pers. obs.).

Table 6-1: Narrative of the environmental history of Wainono Lagoon based on palaeolimnological data and historical information contained in this report

Zone	Approximate dates	Narrative based on palaeolimnological analyses and historical information
1	Pre-1850	**Interpretation:** Large, intact coastal wetland area with areas of quaking (floating) wetland **Palaeo-limnological evidence:** • sediments clay and silt, no sand • no diatoms • few indicators of freshwater environment (sponge, charophyte, caddis) • no charcoal
2a	1850 to 1880	**Interpretation:** European settlement, fire clearance of upper catchment, wetlands largely intact **Palaeo-limnological evidence:** • sediments with high component of sand-size particles • abundant of freshwater charophytes (*Chara* and *Nitella* spp., freshwater sponges, *Daphnia* sp. • diatoms indicate freshwater environment • no charcoal
2b	1880 to c. 1910	**Interpretation:** Similar to Zone 2a, but with less erosion from upper catchment **Palaeo-limnological evidence:** • similar sediment to Zone 2a but with less sand-sized particles
2c	c. 1910 to 1960s	**Interpretation:** Artificial opening to sea (Waihao Box), lowered lake level, increasing marine influence, wetland vegetation burned, wetland drainage, agricultural encroachment, shift to seagrass community **Palaeo-limnological evidence:** • abundant charcoal • loss of sponges, charophytes and *Daphnia* • introduction of *Hyalodiscus scoticus* diatoms indicating brackish conditions • abundant fibrous plant matter (*Ruppia*/seagrass detritus?)
3	1960s to present	**Intepretation:** Loss of macrophytes, fine silts/muds enter the lake, turbid and eutrophic brackish lake with few macrophytes, continued marine influence and low lake levels, continued catchment modification by fires **Palaeo-limnological evidence:** • abundance of diatoms preferring brackish conditions • loss of plant detritus • abundant chironomid head capsules • abundant charcoal • low organic matter content • increased clay content

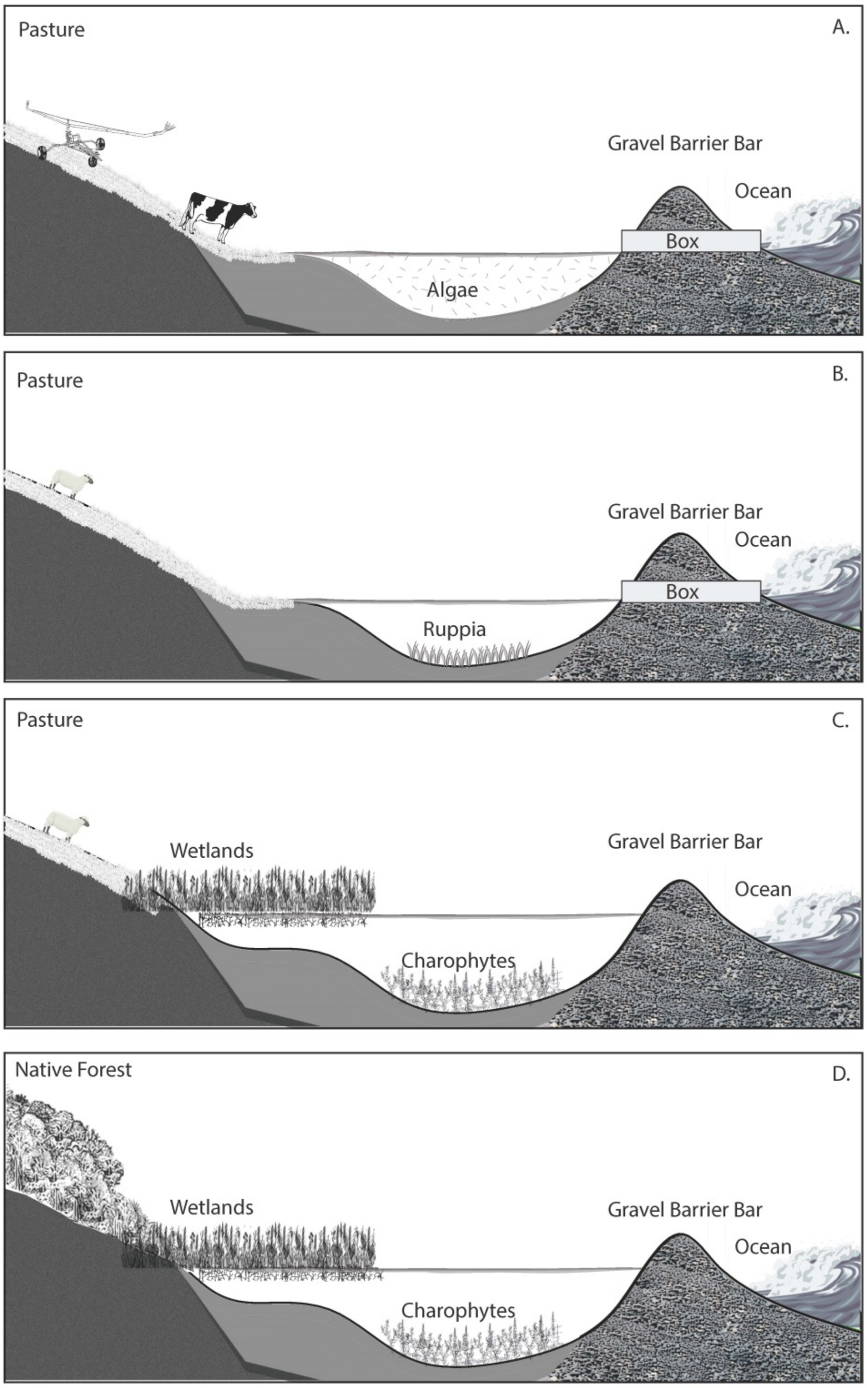


Figure 6-1: Schematic diagram of the inferred environmental history of Wainono Lagoon. A. Condition since the 1960s (Zone 3). B. Condition from c. 1910 to the 1960s (Zone 2c). C. Condition from the 1850 to c. 1910 (Zone 2a, b), D. Condition prior to European settlement in the catchment in the 1850s (Zone 1). See Table 6-1 for explanations

The inferred history presented here shows that there have been three major changes to Wainono Lagoon in the past 160 years.

- First, the clearance of the upland areas caused a pulse of eroded soil to enter the lake, first fine particles, then coarse particles.
- The second major event was the artificial lowering of the water level by construction of the Waihao Box in 1910.
- The third was the removal of wetland areas around the lake and the intensified development of the lake margins for farming - a process that has progressed from 1910 to today.

Water levels, sedimentation rate and nutrient loading are key factors determining the state of Wainono Lagoon and its surrounding wetlands. The coastal lakes of New Zealand's South Island are prone to infilling (Cosgrove, 2011; Schallenberg *et al.,* 2012). Although our investigation does not suggest that there were major changes in the sedimentation rate over the last 100 years, the lake bed has been progressively receiving more fine clays since land use intensification began (see Fig. 5-2).

The recent decline in water quality in Wainono Lagoon is not surprising given the anthropogenic pressures that have been placed on the lake ecosystem over time. The re-establishment of macrophyte beds in the lake would improve water quality, biodiversity and ecosystem services. After years of no reports of macrophytes in the lake, the surprising observation of seedlings of *Ruppia*-like plants in Wainono Lagoon in the summer of 2012-2013 suggests that the lake is clinging to an ecological threshold or tipping point and that successful restoration to a state with stable and healthy macrophyte beds, clearer waters and a diverse and productive aquatic food web could still be achievable.

7 Acknowledgements

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