

Anthropogenic impacts on Waituna Lagoon: Reconstructing the environmental history



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Abstract

Waituna Lagoon is a shallow temperate coastal lagoon in Southland, New Zealand. The 1,350 hectare Waituna Lagoon and associated wetland system is of national and international importance for its unique ecology and the cultural values placed upon it. Waituna is opened to the sea ca. 1-2 times annually, during which time it becomes estuarine. This opening regime has been artificially managed since 1908, with an unknown impact on the lagoon. Since 2007, Waituna appears to have experienced rapid degradation and eutrophication, possibly due to intensification of farming in its catchment. It has rare, extensive beds of the seagrasses *Ruppia megacarpa* and *Ruppia polycarpa*, which have been lost from many similar systems due to eutrophication and sedimentation. Waituna Lagoon is currently under active management to preserve its unique ecology, and its restoration to a more natural state is being considered.

This study aims to reconstruct Waituna Lagoon's natural opening regime and *Ruppia* dynamics, as understanding the natural ecosystem is important for restoration. The hypotheses are: (1) that under a natural opening regime, environmental variations within Waituna Lagoon were less frequent but more extreme; (2) that *Ruppia* was not present in Waituna Lagoon under a natural opening regime; and (3) that *Ruppia* was not dominant in Waituna Lagoon under a natural opening regime.

Three push cores (130, 83 and 64 cm length) were collected from the sheltered Shand Bay and from the wind-exposed, deepest site in the main lagoon. Analyses of sedimentary material included organic and water content, sediment density and grain size, ^{210}Pb , charcoal, indicator pollen, foraminifera and microfossils. Images of the cores were taken via x-ray and the Geotek Multi-Sensor Core Logger.

^{210}Pb dating of the sediment was unsuccessful, but the approximate date of transition to an anthropogenically modified system was inferred to occur at ca. 50 cm depth in Shand Bay using profiles of indicator pollen and charcoal.

The historical opening regime was reconstructed using strata of elevated sand content to indicate open (marine) phases and strata of elevated organic content to indicate closed (freshwater) phases. Hypothesis one was supported. Under a natural opening regime phases of marine and terrestrial influence appeared to be more pronounced, and

potentially lasted for longer periods of time. After ca. 1900 the sediment data indicated a higher frequency of phase changes inhibiting lagoon equilibration. An exception was the most recent sediments, which suggested a marine-influenced phase.

Ruppia inhabited Waituna Lagoon under a natural opening regime, and circumstantial evidence suggests that it may have been more dominant at times under the natural opening regime. Hypotheses two and three were rejected. *Ruppia* pollen was more abundant when the lagoon was open, possibly due to increased light availability.

Sediment chronologies are not consistent across Waituna Lagoon. Sediment characteristics differ between the deeper, wind- and tide-exposed mid-lake and shallow, sheltered Shand Bay sites. Sediment strata in the cores from the two sites could not be correlated, indicating that sediment dynamics at the two sites differed markedly. Sediment deposition in the lagoon is highly episodic and appears to derive from diverse sources, making it difficult to accurately reconstruct timelines related to changes in sedimentation and lagoon conditions.

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"...No man is an island, entire of itself..." – John Donne (Meditation XVII)

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1. General introduction

1.1 Lake and wetland restoration

Human-induced environmental changes are impacting ecosystems throughout the world, including coastal systems such as wetlands and lagoons (Thompson and Ryder, 2003; Conti, 2008). The resilience of these systems is affected by their ontogeny (Michener *et al.*, 1997). The persistence of many such systems is under threat due to anthropogenic environmental change, including human encroachment (Michener *et al.*, 1997; Karr and Chu, 2000).

Estuaries, wetlands and coastal lagoons are dynamic environments that are influenced by changes in the surrounding catchment (McLay, 1976; van der Valk, 2006). Of all estuary types, intermittently closed and open lakes and lagoons (ICOLLs) such as Waituna Lagoon are the most vulnerable to human impact (Boyd *et al.*, 1992). Many coastal lagoons are threatened because of anthropogenic nutrient enrichment, accelerated sedimentation and human-induced hydrological changes (Webster and Harris, 2004). These threats are evident in Australia and New Zealand and place large pressure on surviving wetland systems such as Waituna Lagoon and wetlands (Cadmus, 2004; Webster and Harris, 2004). Over 50% of the global human population is projected to live within 80 km of the sea by 2025, increasing the value and pressure placed upon these systems (Granek *et al.*, 2010).

New Zealand is characterized by many inland water bodies which are recognized as nationally or internationally important (Ministry for the Environment, 2004). However, due to pressures caused by the growing human population and continued economic reliance upon farming, New Zealand is globally ranked among nations with the highest rates of wetland loss (Peters, 2010). In the last 150 years approximately 90% of New Zealand's wetland area has been lost through drainage in land reclamation projects (Peters, 2010). With valuable services such as disturbance regulation, water quality enhancement and fish production provided by aquatic ecosystems, their conservation and restoration is vital (Granek *et al.*, 2010; Peters, 2010). Rapport (1998, cited in Lackey, 2001) wrote that “the articulation of ecosystem health goals and indicators of performance to achieve these goals is a necessity if the future for humankind is to be viable”.

The term “health” is frequently employed when discussing ecosystem management and restoration goals (e.g. Ward *et al.*, 2003; Palmer *et al.*, 2005; Walsh, 2006). While convenient, the term is contentious as it is difficult to define and many scholars believe it is too emotive for use in Western positivist science (Scrimgeour and Wicklum, 1996; Meyer, 1997; see also discussion in Lackey, 2001). It also implies that ecosystems have an optimal condition (McGlade, 2002).

Despite the dangers associated with using the term “health” it can be useful in initiating dialogue (Meyer, 1997; Boulton, 1999) and implies an ecosystem-level approach to management (Scrimgeour and Wicklum, 1996). This dialogue and holistic approach are vital components of effectively managed ecosystems (Rapport *et al.*, 1999; Smol, 2008). A point of conflict in this management however is the difficulty in formulating a mutually agreeable definition of ecosystem “health” and attendant restoration goals (Meyer, 1997). Such definitions are often contentious within and between different lobby groups, with different viewpoints based upon different relationships with the environment.

Meyer (1997) defined a “healthy” ecosystem as “an ecosystem that is sustainable and resilient, maintaining its ecological structure and function over time while continuing to meet societal needs and expectations”. Smol (2008) stated that “a healthy ecosystem is one that has similar characteristics to those that were present before significant human impacts occurred”. This definition by Smol (2008) is accepted for use within this report. Both definitions demonstrate the importance of having long-term knowledge of the ecosystem in question when setting restoration goals.

Often data on ecosystem health spans at most several decades, while local cultural knowledge may provide anecdotal evidence spanning hundreds of years (e.g. Green *et al.*, 2010; Pareek and Trivedi, 2011). Paleolimnology provides a longer record, potentially reflecting conditions from the formation of the ecosystem to the present day (Horrocks *et al.*, 2007; Nichol *et al.*, 2007). Thus it enables the study and management of freshwater ecosystems at a range of timescales, presenting an invaluable tool for lake and wetland restoration (Gorham and Rochefort, 2003; Smol, 2008).

Smol (2008) identified three questions which need to be answered to effectively restore an ecosystem:

1. What were the ecological conditions before anthropogenic disturbance? Often called the “reference condition”, when known these characteristics are often used in setting restoration targets. Without this knowledge it may be difficult to determine appropriate or realistic goals.
2. How naturally dynamic is the ecosystem? Through knowing the natural variability of an ecosystem it is possible to interpret observed trends with more accuracy and determine their true significance. For example, a study may show the organic and water content of sediments in a coastal lagoon over time, which would demonstrate whether deep water anoxia is a naturally occurring phenomenon.
3. What is the critical level of stress the ecosystem may endure before there is evidence of negative symptoms? For example, what is the level of nutrients a lake may assimilate before algal blooms appear? This question may not be relevant in all ecosystems, depending on the level of degradation which occurred before the restoration project began. In the best case scenario symptoms of ecosystem stress such as the occurrence of algal blooms and fish kills will not yet be present.

Paleolimnological tools may be used to answer each of these questions, informing effective ecosystem management and restoration. This thesis focuses upon answering the first two questions for specific dynamics within Waituna Lagoon.

1.2 Paleolimnology

Paleolimnology is a physical, chemical and biological science which reconstructs past environmental and ecological conditions through interpreting sedimentary records of inland aquatic ecosystems (Smol, 2008). Although generally focusing on freshwater systems, paleolimnology also encompasses brackish and saline ecosystems such as estuaries and salt lakes (Reeves, 1968). Such ecosystems may have become terrestrial, for example Hicks and Nichol (2007) studied an infilled wetland at Kowhai Beach, Northland,

New Zealand; and many ancient lake basins have also been studied (e.g. Sarmiento *et al.*, 2008; Chetel and Carroll, 2010).

Sedimentary records are informative as they are products of the environments in which they were deposited (Claessens *et al.*, 2006). Sediment sinks in inland aquatic ecosystems are less prone to subaerial erosion than terrestrial environments (Brunsdon, 1993) and often create long-term records of environmental processes within their catchments (Claessens *et al.*, 2006; Williams, 2011). These records include ecological and climatic changes as well as high magnitude events such as landslides (Cochran *et al.*, 1999) and volcanic eruptions (Eden and Froggatt, 1996). Paleolimnological studies yield insight into the formation of these ecosystems, how they have changed over time (Nichol *et al.*, 2007) and the scale and timings of these processes (Claessens *et al.*, 2006).

Ecological and environmental changes are often manifested in altered sedimentary processes, salinity and vegetation (pers. obs., e.g. Elliot *et al.*, 1997). Known ecological niches of taxa preserved within sediments can be used as proxies for environmental changes (Williams, 2011). For example, pollen, phytoliths and macrofossils have been used to reconstruct historical distributions of plant species, the environmental tolerances of which can indicate environmental, ecological and climatic conditions (Armour and Kennedy, 2005; Deng *et al.*, 2006).

The interpretation of these records can be difficult (e.g. Li *et al.*, 2008) but is essential. Sedimentary records preserved in inland aquatic ecosystems demonstrate ongoing climatic change (Alloway *et al.*, 2007). Understanding how these ecosystems have changed in relation to environmental variables enables researchers to predict responses to future climatic changes. The enhanced management stemming from this knowledge may help maintain the integrity of these ecosystems as climatic variability increases.

The same is true for ecosystem changes as a result of anthropogenic pressure, the magnitude of which is increasing. There is an increased demand for resources from freshwater ecosystems, and an increased pressure for land, often leading to wetland drainage (Turner *et al.*, 2000; Carlson, 2011). Appropriate management of these ecosystems requires knowledge of their historical conditions, and an understanding of how they have already changed in response to anthropogenic impacts (Williams, 2011). In the words of Winston Churchill, "The farther backward you can look, the further forward you are likely to see" (1874-1965; cited in Smol, 2008).

2. New Zealand's coastal lagoons, estuaries and wetlands during the Holocene

2.1 Introduction

New Zealand is a small archipelago of mountainous islands situated in the South Pacific Ocean. Despite its small landmass, New Zealand has one of the longest coastlines in the world (Hume *et al.*, 1992). This is marked by numerous features such as estuaries, inlets and harbours as well as backbarrier lagoons, swamps and wetlands. New Zealand is highly sensitive to global environmental and atmospheric change due the Southern Hemisphere circumpolar westerly circulation vortex (Alloway *et al.*, 2007) and the influence of the Antarctic circumpolar current. The long coastline and mountain ranges amplify the effects of these systems (Alloway *et al.*, 2007), resulting in a unique environment for coastal research.

This chapter focuses on changes in New Zealand's coastal ecosystems through the Holocene (ca. 11,500 BP¹ – present, Schulmeister and McGlone, 2008), as this is the most relevant to research on Waituna Lagoon. The vegetation, salinity and sedimentation regimes of many aquatic ecosystems (Fig. 1) are discussed, as these factors frequently change over time. The chapter ends with an analysis of historical anthropogenic impacts on sedimentation in a range of aquatic ecosystems in New Zealand, as this places the study on Waituna Lagoon into a stronger national context.

2.2 Formation

New Zealand has undergone significant changes since breaking away from Gondwana approximately 85 - 80 million years ago (Gibbs, 2006; Tennyson, 2010). Its development into the modern archipelago was influenced by a host of physical processes such as tectonic and volcanic activity, sea level fluctuations and weathering (Molloy and Smith, 2002;

¹ BP = Years before present.

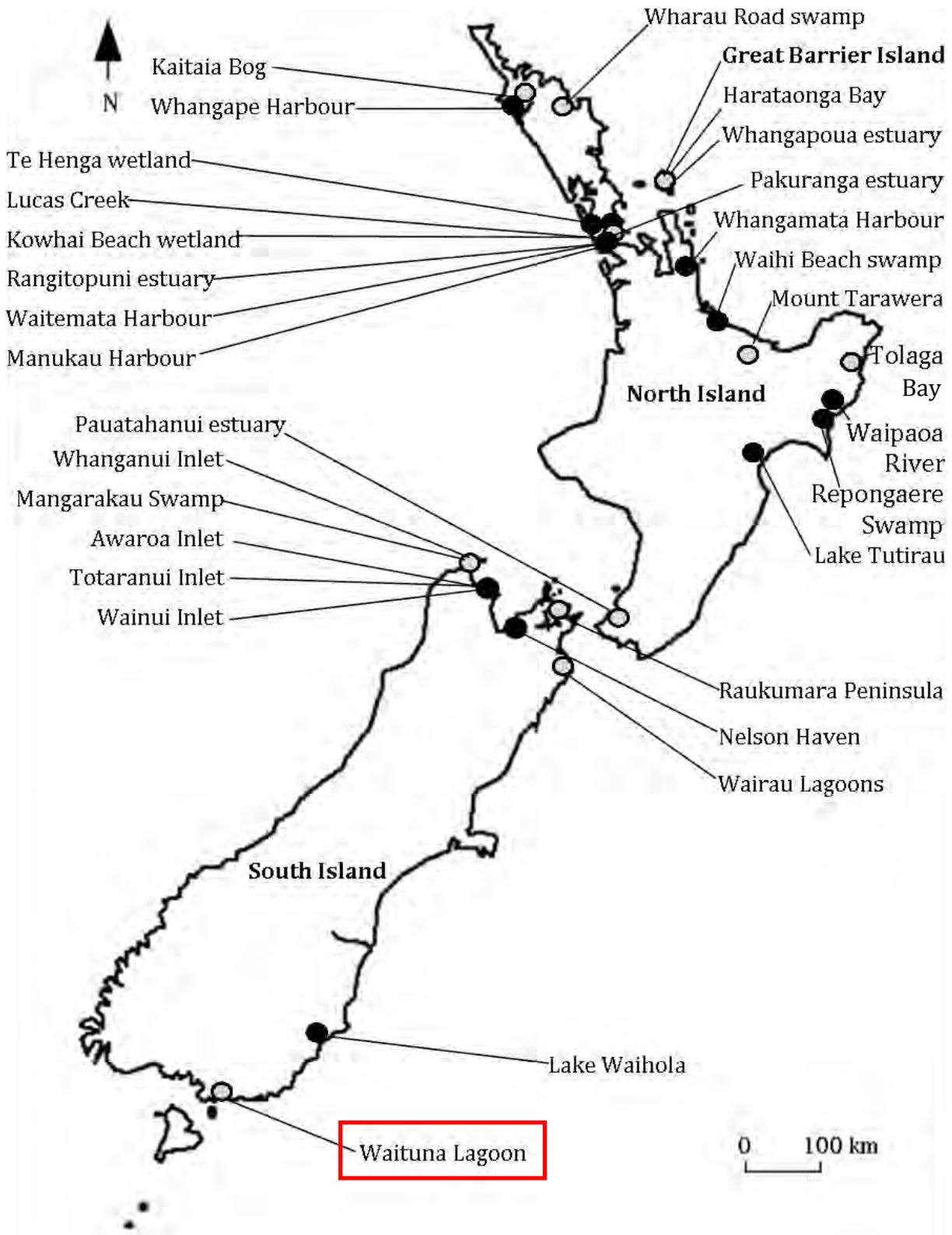


Figure 1: Map of New Zealand, showing places mentioned in this chapter. Black circles indicate the site was included in the meta-analysis described in section 2.6

Hayward *et al.*, 2006; Graham and King, 2008). Eastern Southland is relatively tectonically stable, and lowland areas such as Waituna Lagoon were most strongly affected by sea level changes (Graham and King, 2008; Clement *et al.*, 2010).

New Zealand experienced ca. 50 glacial/interglacial cycles during the Quaternary (Graham, 2008), with attendant sea level fluctuations (Campbell and Hutching, 2007; Fig. 2). The eustatic sea level was ca. 5 m above the present levels ca. 125,000 years ago at the height of the last interglacial period, before falling markedly during the Last Glacial Maximum (ca. 28,000 - 18,000 BP; Stewart and Bidwell, 2008). Around 20,000 years ago sea levels were ca. 125 - 130 m below the present level, and they have generally been rising slowly ever since as the climate warmed, evidence for which can be found all around New Zealand including the Otago/Southland coast (Campbell and Hutching, 2007; Stewart and Bidwell, 2008). During that time Waituna Lagoon did not exist. The river system currently draining into Waituna ran into the sea further south, and the land upon which Waituna is situated was not coastal (Fig. 2).

In the early to mid-Holocene warming (ca. 11,600 – 6,500 BP) the New Zealand climate was similar to that of the present (Alloway *et al.*, 2007). Recent research suggests that the sea levels stabilized at approximately the present level before 7,000 BP (Clement *et al.*, 2010). At this time they reached their maximum level for the Holocene, being a little above the present sea level (Gibb, 1986). This mid-Holocene sea level highstand has been recorded in the southwest Pacific (Woodroffe *et al.*, 1995; Baker and Haworth, 1997, 2000; Nunn, 1998) and may have affected New Zealand (Gibb, 1986; Berryman *et al.*, 1992b; Horrocks *et al.*, 2000a; Hicks and Nichol, 2007) before late-Holocene coastal progradation (Ota *et al.*, 1988). Both the timing and magnitude of this highstand are contested (e.g. Deng *et al.*, 2006; Alloway *et al.*, 2007). Overall, evidence from vegetation, salinity and sedimentation records suggest the mid-Holocene highstand affected New Zealand. Based on overwhelming evidence, the author accepts the strong possibility of this highstand and it is not debated further in this report.

Gibb (1986) calculated a stillstand in the New Zealand sea levels at approximately the present level from 6,500 - 5,000 years ago, followed by regressions and transgressions of less than one metre until ca. 2,000 years ago, when the sea levels stabilized at the present levels with only very minor fluctuations (Gibb, 1986).

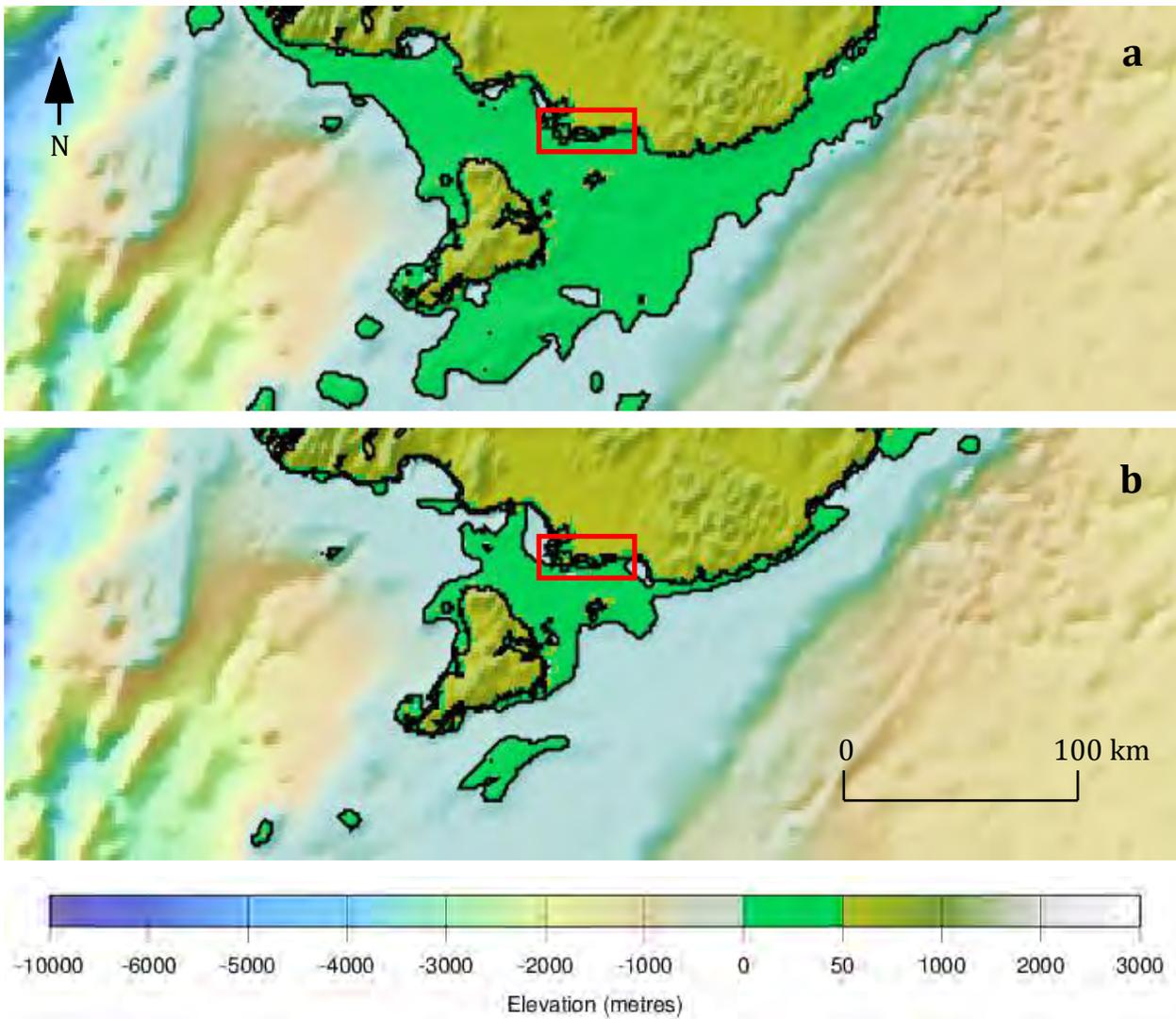


Figure 2: Reconstruction of the projected sea level around the lower South Island, New Zealand at (a) ca. 20,000 BP and (b) ca. 12,000 BP, and their impact on Waituna Lagoon (marked with a red box). Modified from Lee *et al.*, 2003

The late-Holocene (ca. 900 - 500 BP) was characterized by slightly warmer temperatures (Alloway *et al.*, 2007) which coincided with the first anthropogenic environmental impacts on New Zealand (Lowe *et al.*, 2000). These anthropogenic effects are a pronounced feature of the late-Holocene (Molloy, 1969; Elliot *et al.*, 1997, 1998) and have led to the latter part of the Holocene being labelled by some scholars the “Anthropocene”.

Much debate surrounds the timing of human immigration to New Zealand. Recent research based upon dates of the earliest rat-gnawed seeds suggests that humans first immigrated to New Zealand in ca. 1280 A.D, settling in the North and South Islands at approximately the same time (Wilmshurst *et al.*, 2008). This date correlates with the oldest

evidence of anthropogenic extinctions, deforestation, and archaeological sites in New Zealand (Wilmshurst *et al.*, 2008). In most aquatic ecosystems in New Zealand the first evidence of anthropogenic environmental change is not visible until ca. 900 - 600 BP (Elliot *et al.*, 1997, 1998; Hicks and Nichol, 2007).

2.3 Vegetation

The history of vegetation in an area can be inferred from phytolith and pollen analyses from sedimentary records (Horrocks *et al.*, 2000b; Prebble and Schulmeister, 2002). These have been used to determine the distribution and abundance of plant species through time (Armour and Kennedy, 2005). The presence of plant species and communities has been used to indicate both climatic change and catastrophic events (Elliot, 1998). For example, the encroachment of swamp forest into swamps on Great Barrier Island after 3000 BP suggested a change to a drier, windier environment with more frequent droughts and cyclones (Horrocks *et al.*, 1999, 2000a,b,c, 2002a). Generally cooling is indicated by the proliferation of herbaceous pollen with a concurrent decline in tree pollen, and warming by the reverse (Alloway *et al.*, 2007). Less severe cooling or drying is marked by an increase in resilient trees such as podocarps (Elliot, 1998). These climatic inferences are based on the ecology of species in the pollen record and modern studies on succession.

Pollen records vary depending on both local species and the size of the pollen source and sink, with larger pollen catchments resulting in more regionally representative records (Davis, 2000). Armour and Kennedy (2005) reconstructed pollen records in the estuarine margin of Whanganui Inlet and the nearby Mangarakau Swamp northwest of Nelson, New Zealand. Both systems reflected the same large-scale variation in local vegetation, although the swamp recorded more local wetland species. The differences resulted from pollen source, with fluvial transport the dominant source in the estuarine record and the swamp relying on “pollen rain” (Armour and Kennedy, 2005). The study suggested that despite the wider range of sources in estuaries (and attendant increase in preservation bias²) accurate vegetation reconstructions were possible from their records (Armour and Kennedy, 2005).

² For example, fern spores are robust and easily transported downstream. As a result they comprise a disproportionately large percentage of taxa in some New Zealand estuaries such as Whangape Harbour, Northland (Horrocks *et al.*, 2001b).

2.3.1 *Vegetation in the Holocene*

In the early to mid-Holocene warming (ca. 11,600 – 6,500 BP) vegetation communities in New Zealand were very similar to communities with low anthropogenic disturbance today (Alloway *et al.*, 2007) as post-glacial reforestation progressed (Elliot, 1998; Elliot *et al.*, 2005).

The mid-Holocene (after ca. 6,500 BP) was marked by a post-glacial period of climatic cooling and variability (McGlone *et al.*, 1984; Newnham *et al.*, 1989, 1995a,b; Elliot *et al.*, 1997; Alloway *et al.*, 2007). This cool period lasted until ca. 3,800 years ago and resulted in vegetation changes throughout New Zealand's coastal ecosystems (McGlone and Wilson, 1996; Elliot, 1998; Elliot *et al.*, 1998; Horrocks *et al.*, 2002b; Armour and Kennedy, 2005; Li *et al.*, 2008). For example, the Kaitaia Bog in Northland recorded a proliferation in podocarps (Elliot, 1998); while the Whanganui Inlet and Mangarakau Swamp of the Tasman region both recorded a gradual change from podocarp to beech forest, with beech forest dominating by ca. 4000 BP (Armour and Kennedy, 2005). In general, vegetation change during this period involved the increase of cold and drought tolerant species (e.g. Li *et al.*, 2008).

Human arrival in New Zealand resulted in major changes in land-use and attendant vegetation changes (Elliot *et al.*, 1997, 1998), principally through deforestation and the introduction of exotic species (Elliot *et al.*, 1998). At least 75% of all forest cover has been removed in the last 750 years (Wilmshurst *et al.*, 2007). Anthropogenic deforestation occurred at different intensities and timescales throughout New Zealand (Northland ca. 900 BP - Hicks and Nichol, 2007; ca. 600 BP - Elliot *et al.*, 1997), with the majority of deforestation occurring after European settlement to enable pastoral agriculture.

Various studies have demonstrated phases of rapid deforestation associated with Māori and European settlement (McGlone, 1989; Elliot *et al.*, 1997; Claessens *et al.*, 2006). However, such claims must be based on pollen records and not just charcoal deposits as fires may have natural causes (Horrocks *et al.*, 2001a), charcoal is easily transported (Clark, 1988) and charcoal deposits are not necessarily locally or even nationally derived (Butler, 2008). Fortunately most claims of anthropogenic deforestation are based upon a rapid decline in forest taxa, the dramatic increase of *Pteridium esculentum* (bracken fern) and large charcoal deposits (e.g. McGlone, 1978, 1989; Mildenhall, 1979; Hume and McGlone,

1986; Bussell, 1988; Newnham *et al.*, 1989, 1995a; McGlone *et al.*, 1995; Elliot *et al.*, 1995, 1997, 1998; Horrocks *et al.*, 1999, 2000a,b,c, 2001a,b, 2002a,b, 2007; Wilmshurst *et al.*, 2004; Hicks and Nichol, 2007). In some instances this relationship is also supported by an archaeological record (e.g. McGlone and Wilmshurst, 1999). The proliferation of these studies clearly demonstrates a strong relationship between deforestation by fire and an increased abundance of *P. esculentum*.

Māori arrival has been dated by the spread of *P. esculentum* and European by *Pinus radiata* (Monterey pine; e.g. Elliot *et al.*, 1997, 1998; Horrocks *et al.*, 1999, 2007; Wilmshurst, 2004; Hicks and Nichol, 2007). *P. esculentum* is an early successor after fire (Horrocks *et al.*, 2001b). It was present in New Zealand before Māori settlement, but did not become abundant until after extensive Māori deforestation (McGlone *et al.*, 2005). For this reason it is not a good indicator of early Māori arrival, but is useful for dating subsequent large forest fires. *P. radiata* was introduced by European settlers, and became widespread through forestry ventures. These indicator species are valuable in linking anthropogenic activity with the sedimentary record to enable ecological comparison with late Holocene pre-human New Zealand.

2.4 Salinity

Salinity is an indicator of oceanic influence and can be used to track the historical progression of coastal systems from marine to freshwater and vice versa (e.g. Gammon, 1995). This is principally studied through geochemical records and proxies. Common proxies are diatoms and foraminifera as their distribution is principally influenced by water level and salinity, respectively (Hayward *et al.*, 2004a; Claessens *et al.*, 2006; see discussion in Southall *et al.*, 2006).

Accurate interpretation of these records depends upon detailed knowledge of the current ecology and distribution of species in similar ecosystems in New Zealand (Hayward *et al.*, 2004a, 2010a; Claessens *et al.*, 2006). For example, foraminifera and ostracods were used to reconstruct the history of Marlborough's coastal Wairau lagoons (Hayward *et al.*, 2010b). The lagoons were formed by changes in sea levels, sedimentation and subsidence, with the subtidal marine bay changing into a sheltered, semi-closed lagoon. This was temporarily divided into three lagoons by the patterns of infilling (Hayward *et al.*, 2010b).

The high degree of environmental specialization exhibited by diatoms and foraminifera can present an equally specific description of the ecosystem and how it has changed through time (Hayward *et al.*, 2004a, 2010a). In addition, preserved salt-marsh foraminifera are proxies of sea level change and subsidence (Hayward *et al.*, 2007, 2010a; Leorri *et al.*, 2010). They can be used to predict sea level elevations with a very small error, for example Southall *et al.*, (2006) found an error of ± 5 cm.

2.4.1 Salinity in the Holocene

Changes in the sedimentology and the assemblages of foraminifera, macrofauna and diatoms were used to identify four stages of development in the northeastern Raukumara Peninsula, Marlborough (Wilson *et al.*, 2007). The stages were: (1) an estuarine channel, (2) a lower intertidal estuarine system, (3) a fluvial channel, then (4) a transition to an estuary (Wilson *et al.*, 2007). Changes in the species assemblages of foraminifera and diatoms were instrumental in these deductions, as they indicate changes in salinity and water depth over time. For example, the freshwater fluvial zone lacks foraminifera and marine diatoms, whereas in the transitional zone diatom species assemblages suggested a brackish ecosystem (Wilson *et al.*, 2007).

Changes in the diatom record at Kowhai Beach wetland, Auckland, were used to demonstrate the possibility of a mid-Holocene highstand (Hicks and Nichol, 2007). Following this highstand coastal progradation was indicated at a wetland at Te Henga, Auckland, by a change in the foraminiferal species assemblage (Claessens *et al.*, 2006). Foraminifera in the Waitemata Harbour, Auckland, show major changes in species composition since human colonization in ca. 700 BP, largely as a result of decreased salinity (Hayward *et al.*, 2004a). This probably stems from land use changes in the catchment, with deforestation increasing runoff, and urbanisation increasing the sedimentation rate and heavy metal input (Hayward *et al.*, 2004a).

There have been salinity changes in New Zealand's aquatic ecosystems during the Holocene, as demonstrated by these studies. The direction of these salinity changes were largely determined by sea level fluctuation, subsidence and sedimentation, the latter of which is often increased by anthropogenic activities (e.g. Kettner *et al.*, 2009).

2.5 Sedimentation

Sediment deposits in ecosystems such as swamps and estuaries record environmental processes in their catchments (Claessens *et al.*, 2006; Williams, 2011). Sedimentation rates and estuarine infilling are driven by the erosion of terrestrial sediment, as well as water movement, submarine geomorphology and sea level changes (Deng *et al.*, 2006; Hicks and Nichol, 2007). Sediment transport processes become more important as these ecosystems infill with sediment (Horrocks *et al.*, 2001b).

Understanding the processes of sedimentation is important for paleolimnological studies. Wetlands upstream may trap sediments before they reach lakes or lagoons (Cochran *et al.*, 1999), and sediment erosion or very slow accretion may lead to gaps in the record (Elliot, 1998). This can lead to major events not being well represented in the sedimentary record (Cochran *et al.*, 1999) and necessitates careful selection of core sites.

Natural and anthropogenic disturbances play a key role in sedimentation in aquatic ecosystems, although the relative importance of these disturbances is variable (Deng *et al.*, 2006, Claessens *et al.*, 2006). For example, landslide events may cause rapid sedimentation through dramatically increasing the loose sediment available for deposition; this sediment is rapidly transported to aquatic ecosystems during periods of high rainfall and flooding (Glade, 2003; McFadgen and Goff, 2005; Claessens *et al.*, 2006). This phenomenon is magnified by deforestation (Claessens *et al.*, 2006) which may be natural or anthropogenic, and by earthquakes (McFadgen and Goff, 2005). Anthropogenic influences may be more significant than even high magnitude earthquakes however, as earthquakes mainly generate sediment near the uplift zone (Goff, 1997). Natural deforestation may be initiated by fires started by volcanic eruptions or lightning (see Glade, 2003) and severe weather events such as cyclones (Elliot *et al.*, 1997). Cyclones are thought to have been more common in the Last Glacial Maximum (Horrocks *et al.*, 2000a; Elliot *et al.*, 2005).

The erosion of soils from catchments particularly during flooding events has led to infilling (to various levels) in many coastal ecosystems in New Zealand, such as Te Henga wetland (Claessens *et al.*, 2006), Whangapoua estuary (Deng *et al.*, 2006) and Whangape Harbour (Horrocks *et al.*, 2001b).

2.5.1 Sedimentation in the Holocene

In the mid-Holocene raised sea levels resulted in the deposition of fine sediment in estuaries and similar ecosystems (Horrocks *et al.*, 2000a). For example, sedimentation levels in Wellington's Pautahanui estuary were very high (11 mm yr^{-1}) at ca. 8,000 BP when sea levels were rising rapidly (Hume *et al.*, 1992). In contrast, sedimentation at the same estuary was very slow (2 mm yr^{-1}) from 3,610 - 1,360 BP when sea levels were stable at approximately the current level (Hume *et al.*, 1992). Following the mid-Holocene sea levels decreased slightly (Ota *et al.*, 1988; Claessens *et al.*, 2006). At Te Henga wetland in Auckland this resulted in sedimentary changes with a reduction in the average grain size, as well as a possible salinity change in ca. 6000 BP (Claessens *et al.*, 2006).

Sedimentation in several coastal ecosystems increased around 700 - 600 BP, which has been correlated in many areas with the arrival of Māori (Lowe *et al.*, 2000) and anthropogenic burning of forests (Deng *et al.*, 2006; Ogden *et al.*, 2006). Examples include Whangapoua estuary (Deng *et al.*, 2006), Wharau Road Swamp (Elliot *et al.*, 1997) and the upper Waitemata Harbour (Hume and McGlone, 1986). In Lucas Creek, a shallow tidal creek which feeds into the Waitemata Harbour, Hume and McGlone (1986) found low levels of deforestation and sedimentation accompanied Māori settlement. The sedimentation rates tripled with the advent of European farming, before decreasing slightly to the current rates (Hume and McGlone, 1986). This difference in erosion is largely due to the occupation of different areas. Early Māori were hunter-gatherers who practiced limited agriculture in lowland areas, while European settlers also farmed livestock on slopes (Glade, 2003).

The relationship between anthropogenic deforestation and increased sedimentation due to erosion has been implicated in many coastal ecosystems around New Zealand (e.g. Elliot *et al.*, 1997; Claessens *et al.*, 2006; Deng *et al.*, 2006; see also examples in Glade, 2003). More recently sedimentation rates have been further increased by urbanisation (Hayward *et al.*, 2004a). Low-energy ecosystems are particularly susceptible to anthropogenic impacts overriding natural processes of sedimentation (Horrocks *et al.*, 2007).

Despite the strength of anthropogenic impacts on coastal lagoons, estuaries and wetlands in New Zealand, not all recent changes have been due to anthropogenic factors. For example, a large change in sediment infilling in a back-dune wetland near Tolaga Bay, Gisborne, was most likely the result of oceanic influence during a severe storm (Horrocks *et*

al., 2008); and the enclosed Harataonga Bay of Great Barrier Island appears to have been impacted by a tsunami (Nichol *et al.*, 2007).

2.6 Historical anthropogenic impacts on sedimentation in New Zealand's aquatic ecosystems

2.6.1 Introduction

With a relatively short history of human occupation (McGlone, 1989), it is comparatively simple to study the impacts of human settlement on New Zealand's aquatic ecosystems (Glade, 2003). Many studies have shown a relationship between anthropogenic activities such as land use changes and sedimentation in New Zealand's aquatic ecosystems (section 2.5.1). Through analysing published literature, this study aims to establish the impact of anthropogenic settlement on sedimentation in New Zealand's coastal ecosystems. It was hypothesized that the sedimentation rate increased with increasing anthropogenic impact. More specifically, it is hypothesized that sedimentation rates increased following Māori settlement and again after European settlement.

2.6.2 Methods

This study is a comparative analysis of previously published data from sediment cores collected from coastal and lowland aquatic ecosystems in New Zealand. All pre-human sediment samples are from strata that post-date the proposed mid-Holocene highstand. The four date categories used in this study are pre-human (6,500 - 700 BP), Māori (700 - 200 BP), European (200 - 50 BP) and present (50 - 0 BP). The specific dates vary slightly with site as they rely upon existing publications, and sites were colonised at different times.

As this study seeks to quantify changes induced by anthropogenic activities, articles with strong confounding factors such as seismic activity and discernible bioturbation were excluded from analysis. For example, Te Henga wetland was excluded as it had been clearly influenced by earthquakes (Claessens *et al.*, 2006). All other studies which quantified sedimentation changes in these ecosystems for at least two of the specified time periods were included. Two cores were included from Whangamata Harbour and Whangapoua

estuary as they recorded effects from two different catchments (e.g. the study on Whangapoua estuary included cores from freshwater and estuarine swamp sites).

Sedimentation rates were obtained from eighteen sites representing sixteen aquatic systems, distributed throughout the North and South Islands (Fig. 1; Table 1). If ranges for sedimentation rates were reported, the midpoint of the range was used in the analysis. The overall mean rate of sediment infilling among aquatic ecosystems and its standard error were calculated for each time period. Paired t-tests were conducted using the Minitab statistical software (Minitab Inc., United States of America) for each possible combination of time periods.

2.6.3 Results

Data used in the meta-analysis is displayed in Table 1. The sedimentation rates in New Zealand's aquatic ecosystems have increased over time (Fig. 3). Although the rate of sedimentation among aquatic systems increased during the period of Māori settlement (Fig. 3) this increase was not significant ($P = 0.102$). The sedimentation rate during the period of European settlement was significantly higher than the sedimentation rates during the pre-human period ($P = 0.002$) and the period of Māori settlement ($P = 0.007$).

The mean and variability of recent sedimentation rates are greater than those for other time periods, but the high variability prevents this trend from being statistically significant (T-test versus pre-human settlement: $P = 0.130$; T-test versus Māori settlement: $P = 0.108$; T-test versus European settlement: $P = 0.144$).

2.6.4 Discussion

Sedimentation in New Zealand's aquatic ecosystems has increased over time, confirming that this increase is correlated with increasing human impact (Fig. 3). However this is only significant for European land use changes, as an increase from both pre-human and Māori conditions. This may be due to the small sample size, although the literature search on which this meta-analysis is based collected all available relevant data.

Table 1: Sites used in the meta-analysis of sedimentation in New Zealand aquatic systems with average sedimentation (mm/yr). The approximate time ranges are: pre-human 6,500-700 BP, Māori 700-200 BP, European 200-50 BP and present 50-0 BP

Location	Pre-human (mm/yr)	Māori (mm/yr)	European (mm/yr)	Present (mm/yr)	Reference
Awaroa Inlet	0.99	0.85	1.86	2.66	Goff and Chagué-Goff, 1999
Lake Tutira	1.95	-	13.0	-	Page and Trustrum, 1997
Lake Waihola	-	-	5.1	6.0	Schallenberg <i>et al.</i> , unpubl. data
Lucas Creek	1.5	1.0	3.0	2.0	Hume and McGlone, 1986
Manukau Harbour	1.5	1.0	3.0	2.0	Hume and Dahm, 1991
Nelson Haven	0.18	0.06	1.3	4.5	Hume and Dahm, 1991
Pakuranga Estuary	0.35	0.4	1.2	-	Swales <i>et al.</i> , 2002
Rangitopuni Estuary	0.035	1.0	1.7	7.5	Hume and McGlone, 1986
Repongaere Swamp	0.3	0.3	3.7	-	Wilmshurst <i>et al.</i> , 1999
Totaranui Inlet	0.34	2.17	1.56	2.33	Goff and Chagué-Goff, 1999
Waihi Beach Swamp	0.11	0.21	-	-	Newham <i>et al.</i> , 1995a
Waipaoa River System	1.43	1.6	2.2	5.5	Kettner <i>et al.</i> , 2009
Wainui Inlet	-	1.7	2.7	3.0	Goff and Chagué-Goff, 1999
Whangamata Harbour	0.06	0.28	11.0	34.0	Hume and Dahm, 1991
Whangamata Harbour	0.35	0.31	6.6	-	Hume and Dahm, 1991
Whangapoua Estuary	0.18	1.1	1.31	-	Ogden <i>et al.</i> , 2006
Whangapoua Estuary	0.55	2.4	1.75	-	Ogden <i>et al.</i> , 2006

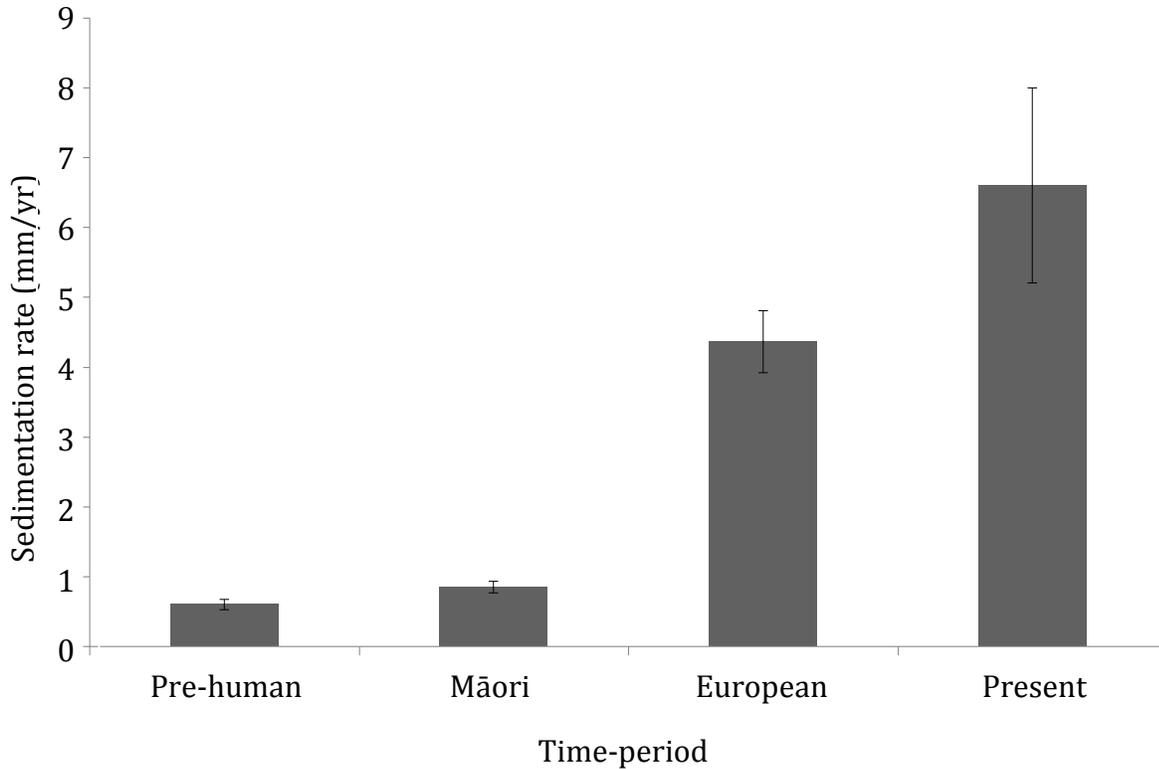


Figure 3: The mean sedimentation rates (\pm standard error) of New Zealand's aquatic ecosystems with time-period. The date ranges and numbers of studies included are: Pre-human 6,500-700 BP, $N = 17$; Māori 700-200 BP, $N = 18$; European 200-50 BP, $N = 18$; and Present 50-0 BP, $N = 11$

Early Māori tribes had a large impact on the New Zealand landscape, principally through widespread deforestation via burning to facilitate their hunter-gatherer lifestyles (Ogden *et al.*, 2006; Lowe, 2008). This deforestation would have increased sedimentation through destabilizing slopes and increasing sheet erosion (Ogden *et al.*, 2006). Despite this the sedimentation increase is not significantly different to the pre-human background sedimentation rate. This may be due to periodic natural deforestation prior to colonization stemming from events such as earthquake-induced landslides (Berryman *et al.*, 1992a), or natural forest fires caused by lightning or volcanic activity (Newnham *et al.*, 1995a).

A large difference between Māori and European settlers is that Māori settlement was concentrated around the coast, while Europeans also established farms in the inland areas (Glade, 2003). European settlement involved an intensification of land use, including the introduction of grazing animals which were held on freshly burnt and cleared land (Ogden *et al.*, 2006). These activities appear to have contributed to at least quadrupling the mean sedimentation rates. Golubev (1982) stated that agriculture on virgin land dramatically

increases erosion. Thus, intensive farming of ungulates on recently deforested slopes would be expected to greatly increase the probability of erosion and landslides.

The observed trend may be partially influenced by geomorphological processes such as earthquakes, tsunamis, volcanism and sea level rise. However, these are unlikely to have caused the overall trend. The trend was observed inland and on the east and west coasts, yet parts of New Zealand have not been substantially impacted by geomorphological processes within the last 700 years. For example, Mount Tarawera in the Bay of Plenty erupted in ca. 600 BP, depositing ash over ca. 30,000km² (Horrocks *et al.*, 2000a). This deposit did not affect the South Island (Horrocks *et al.*, 2000a), where some sites show a marked increase in sedimentation. Further, the anthropogenic impact on sedimentation in New Zealand's aquatic ecosystems may be more pronounced than it appears as there were many earthquakes in pre-human times (Berryman *et al.*, 1992a).

The Awaroa and Totaranui Inlets of Abel Tasman National Park have been influenced far less than many other aquatic ecosystems in New Zealand (Goff and Chagué-Goff, 1999). Both sites had relatively small permanent Māori settlements, which were followed by small European communities in ca. 1840 - 1880. Low levels of traditional farming continue (Goff and Chagué-Goff, 1999). Despite having experienced low-level anthropogenic impacts these sites are relatively pristine, and may be used as reference sites for comparison with more heavily impacted systems. Sedimentation rates in these sites have not increased as much as sedimentation rates in some more intensively settled sites (Table 1).

Dating paleolimnological records is difficult and carries with it a degree of uncertainty (Battarbee and Renberg, 1990). The limitations associated with this are minimized in this meta-analysis as most studies used indicator species to infer the onset of Māori and European impacts.

A limitation of this study is that sedimentation rates had to be averaged for the statistical analysis. This is a limitation as most studies provided a range of sedimentation values, indicating that it was variable over time and is difficult to precisely quantify. The study was further limited by a small sample size as few paleolimnological studies in New Zealand quantified sedimentation rates. Furthermore, sites were not evenly distributed throughout New Zealand, with many sites in Northland and comparatively few in the South Island (Fig. 1). These issues raise the potential of bias, however despite some clustering sites represent a wide range of micro-climates and may reflect a trend throughout New Zealand.

A site selection and publication bias may have influenced the results. Sites and studies with little apparent change in sedimentation may be under-represented in the literature. However, many studies indicated an “increase” in sedimentation without quantifying this increase (e.g. Nichol *et al.*, 2000), and therefore could not be included in the meta-analysis.

As sedimentation rates are expressed in mm/yr the observed trend may have emerged as a result of dewatering in the deeper sediments. This would bias sedimentation rates as the compaction would result in a greater number of years being preserved in the same length of core, irrespective of the rate of deposition. It was not possible to correct for dewatering within this analysis as raw data was not available from the studies. For sites which published changes in the sediment core water content with depth there was no evidence for dewatering.

Although there are several limitations in completing a meta-analysis the strength of this study is that it provides a general trend, enabling a large-scale pattern to emerge. It is unlikely that any of the potential limitations had a significant impact upon the results.

This analysis demonstrates that human settlement in New Zealand has resulted in large changes to its aquatic ecosystems. Waituna Lagoon in Southland has also been modified, as evidenced by increasing eutrophication. Its natural condition including the hydrological regime and sedimentation rate is unknown. The above results indicate that the sediments of Waituna Lagoon should contain information about its natural condition, and how it changed over time.

3. Waituna Lagoon and wetlands

The Waituna Lagoon and wetlands is a coastal ecosystem situated ca. 20 km south-east of Invercargill on the South Island of New Zealand (Fig. 4; Fig. 5). The shallow lagoon covers ca. 1,350 ha, with the wetlands extending a further ca. 2,200 ha (Thompson and Ryder, 2003). The name “Waituna” is Te Reo Māori for “water of eels”.

The Convention on Wetlands of International Importance especially as Waterfowl Habitat (Ramsar Convention) recognises the Waituna wetlands to be of international importance (Ramsar Convention, 2009), one of only five wetlands in New Zealand to receive such recognition. Formally registered in 1976, Waituna Lagoon and surrounding wetlands were thus one of the first areas in the world to be recognised under the Ramsar Convention. In 2008 the Ramsar Secretariat expanded this area to 19,500 hectares of estuaries and wetlands known as the “Awarua Wetlands” (Ramsar Convention, 2009). Waituna Lagoon is also important nationally for its significance to the Kāi Tāhu Whanui (Thompson and Ryder, 2003), local communities and recreational users.

Waituna Lagoon has been highly modified with hydrological changes, reduced water levels, increased nutrient and sediment inputs, and introduced species.

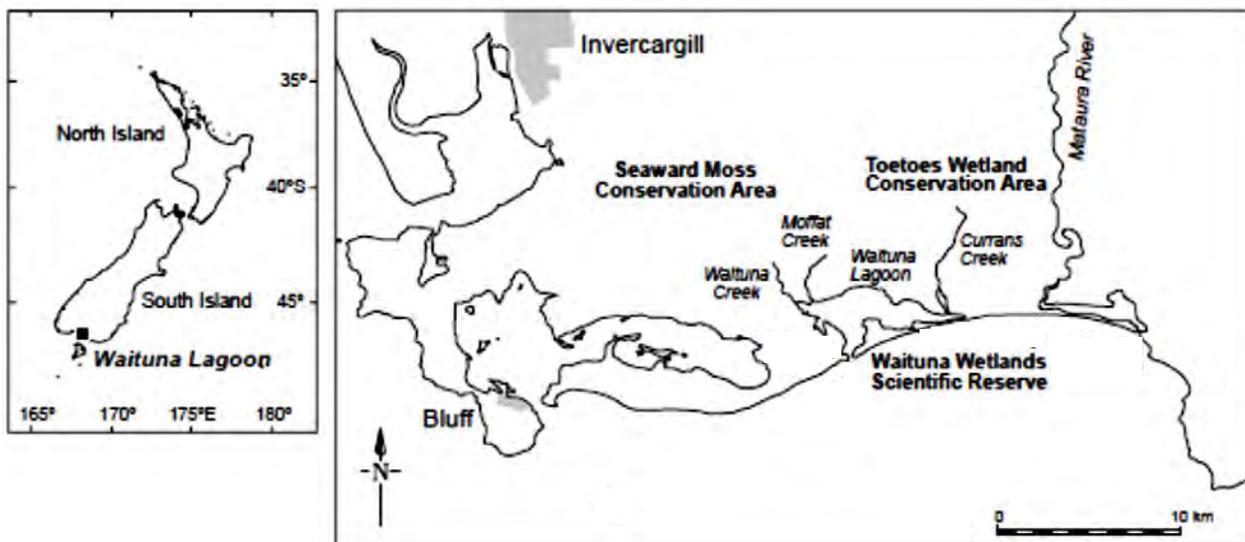


Figure 4: Map showing the location of Waituna Lagoon and wetlands, with local conservation areas noted (modified from Thompson and Ryder, 2003)



Figure 5: A satellite image of Waituna Lagoon (modified from a series of aerial photos of Waituna Lagoon taken in 2008 and provided by Environment Southland)

3.1 Geology and hydrology

Waituna Lagoon is situated on a quartz gravel outwash plain of Late Quaternary to Holocene age (Thompson and Ryder, 2003). Beneath the outwash plain lie mid-Tertiary sediments, including a large amount of lignite (Department of Lands and Survey, 1984). The plain is bounded by Mesozoic greywacke to the north and east, and Permian volcanic intrusions of variable composition to the west (Mossman, 1973; Thompson and Ryder, 2003). The post-glacial deposit on the quartz plain is thick and extensive peat (Johnson, 2001). The area became a wetland during ca. 7,880 - 7,560 BP as sea levels approached the Holocene maximum (Cadmus, 2004). The lagoon has had standing water in it for the last ca. 7,600 - 7,000 years (Cadmus, 2004). Historically Waituna Lagoon was larger than at present, and connected to Awarua Bay to the west³ (Kirk and Lauder, 2000).

Three major streams drain into Waituna Lagoon – Currans Creek (catchment area 5,700 ha), Moffat Creek (1,700 ha) and Waituna Creek (12,555 ha; Thompson and Ryder, 2003; Fig. 3). The total catchment of Waituna Lagoon is 210 km² (Schallenberg *et al.*, 2010) and has a mean annual rainfall of 1,117 mm (Kirk and Lauder, 2000).

3.1.1 Opening Regime

Waituna Lagoon is often separated from the ocean by a sand/gravel barrier bar of ca. 50 m width (Thompson and Ryder, 2003; Figs 5 and 6). Large ocean waves flow over this barrier during storms (Kirk and Lauder, 2000); though the natural method of opening was more commonly high water levels within the lagoon scouring the barrier bar (Johnson and Partridge, 1988). Of this Waghorn and Thomson (1989) wrote:

In early times the lake drained naturally, letting itself out at the east end. When the water level got high, strong westerlies pushed the water to Talls [east] end and the water burst through the shingle bar into the sea. Then gravel would gradually drift across the outlet and block it again.

³ Little is known about the formation of Waituna Lagoon (see Thompson and Ryder, 2003), or the distribution and dynamics of its sediments. Kirk and Lauder (2000) provide information on the formation and physical processes of multiple Waituna-type lagoons in New Zealand, though these findings do not necessarily apply to Waituna Lagoon due to its catchment characteristics.



Figure 6: An aerial view of the Western arm of Waituna Lagoon, facing inland. In the foreground the South Pacific Ocean is separated from Waituna Lagoon by a narrow sand/gravel barrier. This barrier is regularly breached to reduce the lagoon water levels (photo: M. Schallenberg, taken in 2008)

When the barrier is breached the lagoon is connected to the sea and becomes temporarily estuarine, before returning to a freshwater state when closed (Kirk and Lauder, 2000). Intermittently closed and open lakes and lagoons (ICOLs) such as Waituna Lagoon are common in sub-humid, arid and semi-arid environments (Schallenberg *et al.*, 2010). Waituna is the best example of this type of aquatic ecosystem in New Zealand (Thompson and Ryder, 2003), with similar ecosystems being classified by Kirk and Lauder (2000) as “Waituna-type Lagoons”.

Historically the water levels may have reached 4 m above sea level before naturally breaching the barrier bar (Johnson and Partridge, 1998). To maintain a lower water level the barrier is now regularly breached artificially (Johnson and Partridge, 1998; Kirk and Lauder, 2000). The opening regime is currently determined by the water level at the Waghorns Road bridge staff gauge, with water levels rarely allowed to exceed 3 m (Thompson and Ryder, 2003). Artificial management of ICOLL opening regimes is common. For example, over 50% of all ICOLs in Australia’s New South Wales are artificially opened, most often to protect surrounding assets (Haines, 2006).

There are few early accounts which mention the opening regime at Waituna Lagoon before it became modified. One reports herds of cattle having to be driven inland around the lagoon if the waters were open to the sea, as the coastal route became impassable (Waghorn and Thomson, 1989). Another record of the conditions was published by Purchas (1909):

On their left was the sea, and on their right the forest extended for some distance. After a few miles, however, the bush disappeared, and the waters of the Waituna Lagoon opened out in the landward direction. Those who are acquainted with the lagoons on the New Zealand coast are well aware that although they have no regular outlet, their pent-up waters sometimes burst through the barrier which the ocean waves have raised, and rush to the sea with a swift and powerful current. This is what the Waituna Lagoon had just done ... they found the water nowhere more than breast-high, but the bottom was too soft for horses. ... Keeping well out in the lagoon so as to be clear of the current, they circled round for more than half a mile, and at last stood safely on the beach again.

The barrier which separates Waituna Lagoon from the sea has been artificially breached since 1908, most commonly to benefit agriculture but also for recreational activities (Kirk and Lauder, 2000; Thompson and Ryder, 2003). Initially the opening was managed by locals, who opened the lagoon manually using horses and shovels to prevent flooding near their homes and to improve fishing (Waghorn and Thomson, 1989). In 1958 the Department of Lands and Survey (now "Land Information New Zealand") assumed responsibility for the opening regime, which it opened annually using bulldozers (Thompson and Ryder, 2003). The Waituna Control Association was established in 1968 to manage the water levels of Waituna Lagoon, with a strong focus upon drainage to improve surrounding pasture (Thompson and Ryder, 2003). The opening regime is now managed by the Department of Conservation and Environment Southland in consultation with the Waituna Landcare Group, which was established in 2001 to promote the protection of Waituna Lagoon.

The opening regime has been fully managed since 1972, which is the last time Waituna Lagoon breached naturally (Thompson and Ryder, 2003). Based upon available data Waituna Lagoon has since been open for an average of 141 days per year, with a minimum of 0 days (1993) and maximum of 295 (1983; Environment Southland, unpubl. data; Fig. 7;

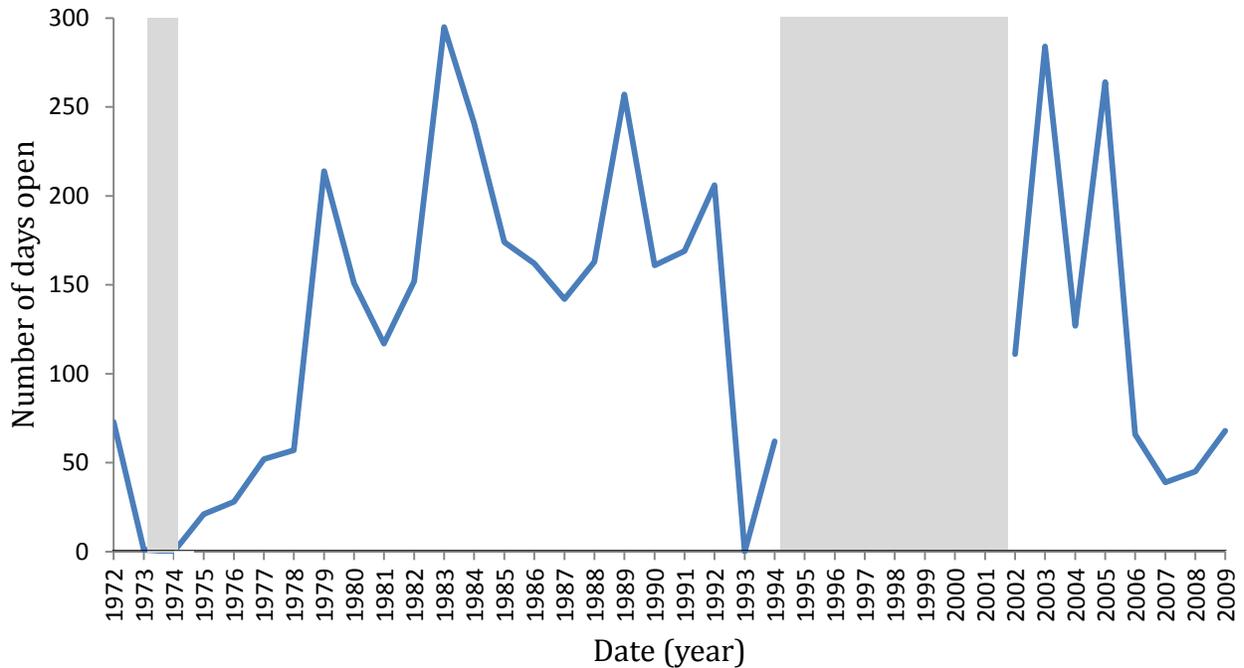


Figure 7: The Waituna Lagoon opening regime, showing the number of days per year the lagoon has been open since becoming fully managed (1972 - 2009). Years with insufficient data are highlighted in grey (data: Environment Southland, unpubl. data)

Table 2). It is believed that use of artificial water level management by cutting the barrier has resulted in the lagoon being open more often than is natural, as the lagoon is opened before it has the opportunity to fill (Thompson and Ryder, 2003).

Since becoming fully actively managed in 1972 Waituna Lagoon has been open for similar lengths of time in each season (Table 2, based upon available data). It has been opened and closed most frequently in winter and spring (June - November) and is not recorded as having closed in summer (December - February). The lagoon is preferentially opened in spring as the ocean currents are generally weaker, making it safer to open the lagoon and release the waters that accumulated over winter (Johnson and Partridge, 1998).

The barrier bar is currently being eroded at an average of 0.77 m/year near the current oceanic entrance to the lagoon, with coastal erosion decreasing the size of Waituna Lagoon by 0.62 ha/year (Kirk and Lauder, 2000). This reduction in size of the barrier bar indicates that the lagoon may become an estuarine ecosystem in the near future.

Table 2: The Waituna Lagoon opening regime for the years 1972 - 1995 and 2002 - 2010. 'Open' includes every month the lagoon was open during (e.g. Feb – July), whereas 'opened' refers exclusively to the opening events. The number of times the lagoon closed in each month excludes the years 1974, 1995 - 2001 and 2010 as limited data was available (data: Environment Southland, unpubl. data)

Month	Number of times open in a month		Number of times opened in a month		Number of times closed in a month	
	<i>N</i>	%	<i>N</i>	%	<i>N</i>	%
January	12	7.2	2	4.4	0	0.0
February	14	8.4	2	4.4	0	0.0
March	14	8.4	0	0.0	2	5.0
April	13	7.8	1	2.2	3	7.5
May	14	8.4	4	8.7	5	12.5
June	14	8.4	6	13.0	10	25.0
July	15	9.0	13	28.3	4	10.0
August	16	9.6	6	13.0	5	12.5
September	17	10.2	7	15.2	3	7.5
October	17	10.2	4	8.7	7	17.5
November	11	6.6	1	2.2	1	2.5
December	10	6.0	0	0.0	0	0.0

3.2 Human activities associated with Waituna Lagoon

It is widely accepted that human habitation of New Zealand came relatively late (e.g. Wilmshurst *et al.*, 2008), with the first settlement occurring around 1280 AD (Alloway *et al.*, 2007).

The first peoples in the South Island were the Waitaha (Anderson, 1998). Kati Mamoe (also known as Ngāti Mamoe) left their North Island settlements and migrated to the South Island in the 15th and 16th centuries, marrying into Waitaha (Anderson, 1998). In the late 17th century Kāi Tahu (also known as Ngāi Tahu) migrated to the South Island from the North Island's east coast (Orbell, 1998). Kāi Tahu established settlements in northern

Canterbury then moved further south, pushing Kati Mamoe southwards as they went (Anderson, 1998). They are now called Kāi Tahu Whanui, and are a collective of people who have inhabited the South Island (including Southland) for a long time (Anderson, 1998).

Kāi Tahu were nomadic, migrating around the South Island seasonally to utilise a range of resources (Anderson, 1998, 2008). The nomadic hunter-gatherer lifestyle was favoured over the subsistence agriculture practiced further north due to Southland's environmental conditions, which do not favour the growth of important crops such as kumara (Anderson, 1998). Instead many sites were used for mahinga kai (traditional resource harvesting; Anderson, 2008).

One such site was Waituna Lagoon, the use of which was strictly governed with access gained through marriage into the appropriate matriarchal line (S. White, pers. comm., 2011). Wetland areas around Waituna Lagoon were also used for body preparation and burial. These areas are considered sacred, and their maintenance is extremely important to Kāi Tahu. The Crown recently recognised Kāi Tahu's "cultural, spiritual, historic and traditional association to Waituna" (New Zealand Parliamentary Council Office, 2008). Archaeological remnants such as ovens provide physical evidence for pre-European use of Waituna Lagoon (Floyd, 1980), but as settlements were only seasonal there was not a large anthropogenic impact upon Waituna Lagoon until later European settlement.

Captain James Cook and crew were the first Europeans to sight the region around Waituna Lagoon, sailing by on 5 March 1770 (Hall-Jones, 1976). In the 1790s European whalers and sealers arrived in New Zealand, establishing camps around the coast including a highly successful whaling station at Maitara Mouth, by Waituna Lagoon (Macintosh, 1975). This began a trend, with groups of Kāi Tahu moving into semi-permanent settlements close to the whaling camps to trade with the European settlers, although the habit of migrating around different sites for resources was maintained (Waghorn and Thomson, 1989; Anderson, 1998).

In 1854 the British Crown purchased the land around Waituna from Kāi Tahu, with European settlement swiftly following (Beattie, 1979). Bluff was one of the first European settlements in New Zealand, founded in 1824 by James Spencer (Hall-Jones, 1976) though settlement in the broader district had already begun (Macintosh, 1975; Beattie, 1979).

There are limited references to the condition and opening regime of Waituna Lagoon before it became heavily modified. One such record of the conditions was made by Belmer (1973):

I had known the area from the Mataura to Awarua Bay as an almost general wilderness. ... This area has some of the poorest land in New Zealand, once marsh, peat swamp and bog, including the Seaward Moss, consisting of dead vegetable matter, and including the Waituna Lagoon which is six miles long, once famous for eels.

The Waituna area was first settled by Scottish pastoral farmers (Beattie, 1979), and it continues to be a farming province to this day. Prior to the 1878 fire, industry around Waituna was based on logging the podocarp forest, with bullock teams dragging logs to timber mills (Floyd, 1980). In the late 19th century the area was caught up in the gold rush, with the Bushy Point Gold Field established at the north of the lagoon in 1866 and operating until 1891 (Waghorn and Thomson, 1989). Bush reserves to the North of Waituna Lagoon provided fuel to operate the gold dredging equipment (Waghorn and Thomson, 1989). The construction of roads and the railway enabled local logging ventures to prosper, with several sawmills established close to the railway station. The Siberia Timber Mill was built on the banks of Waituna Lagoon in 1904 and was successful until it was destroyed by fire in 1907 (Waghorn and Thomson, 1989).

Fire was frequently used to clear land for farming or passage. In 1907 the greatest recorded fire in Southland ravaged the Seaward Bush (Waghorn and Thomson, 1989). After the fire, farming and logging became the main sources of income before being replaced by dairy, sheep and cattle farming (Floyd, 1980; Waghorn and Thomson, 1989; Sorrell, 1999). This transition was enabled in part by drainage and development work by an Unemployment Board work camp during the Great Depression and the Department of Lands and Survey (Thompson and Ryder, 2003).

By 1971 when Waituna Lagoon and wetlands were designated as a Reserve for Wetland Management purposes by the Department of Lands and Survey (Ridell *et al.*, 1988) there were approximately 34 huts on or near the borders of the lake for recreational users (Waghorn and Thomson, 1989). The cleared lands around Waituna are intensively farmed, and the lagoon itself is used for recreational purposes such as hunting and fishing.

3.3 Flora

The floral associations of the Waituna wetlands are unique to New Zealand, with alpine and sub-alpine species present at sea level (e.g. *Donatia novae-zelandiae* and *Carpha alpina*; Thompson and Ryder, 2003). Cushion-bog vegetation (Johnson, 2001), sand-ridge plant communities and locally rare species add to the unique ecosystem (Thompson and Ryder, 2003). Johnson and Partridge (1998) described the floral zonation from the lagoon shore as turf communities, then rushland dominated by *Leptocarpus*, followed by grass, rush and sedge communities. Further from the lagoon is a zone of scrubland dominated by *Phormium tenax* (flax), *Pteridium esculentum* (bracken fern) and *Leptospermum scoparium* (mānuka). *Leptocarpus similes* is the most common species on the lagoon fringes (jointed rush; Johnson and Partridge, 1998).

Despite increasing eutrophication, the waters of the lagoon are still dominated by macrophytes. Macrophytes are key components of many lakes and lagoons (Thomaz *et al.*, 2008), and are often vital for maintaining a healthy ecosystem (Xu *et al.*, 2001; Butterworth, 2008; Li *et al.*, 2010). Macrophytes are autogenic ecosystem engineers (Jones *et al.*, 1994), oxygenating the rhizosphere and affecting light infiltration, sedimentation, water pH, temperature gradients, water movement, and dissolved inorganic carbon concentrations (Carpenter and Lodge, 1986; Kelly and Hawes, 2005). Some macrophytes also purify water by reducing the nutrient and heavy metal load, and may therefore be suitable for treating wastewater (Dhote and Dixit, 2009).

Macrophytes are primary producers and are often a fundamental component of lake and lagoon food webs (James *et al.*, 2000). They provide food, habitat and shelter for multiple tiers of the food web, including serving as a substrate for the growth of epiphytic algae, upon which many invertebrates graze (Petr, 2000; James *et al.*, 2000; Lehtiniemi, 2005). Macrophytes also facilitate high biodiversity through contributing to the ecosystems spatial heterogeneity by increasing the number and range of niches within the habitat (Pelicice *et al.*, 2008; Thomaz *et al.*, 2008).

Macrophytes are so integral to the sustenance of life in lakes and lagoons that in some ecosystems macrophyte bed productivity is correlated to the productivity and biomass of fish, particularly in deep lakes (Jeppesen *et al.*, 1997). In addition habitat complexity caused

by the presence of submerged macrophytes has been linked to the biodiversity and abundance of fish and invertebrates (Rennie and Jackson, 2005; Thomaz *et al.*, 2008; Pelicice *et al.*, 2008). For example, Pelicice and colleagues (2008) found that macrophyte biomass and volume were highly positively correlated with fish biodiversity and abundance in littoral environments in Rosana Reservoir, Brazil.

Within Waituna Lagoon the vegetative communities are diverse and dominated by fresh and brackish water species. The rare *Ruppia polycarpa* (horse's mane weed) and *Ruppia megacarpa* (large-fruit tassel) often dominate the macrophyte communities, particularly when the lagoon is closed, with *Myriophyllum triphyllum* (water milfoil) also abundant in patches (Robertson and Stevens, 2009). The common pattern of zonation with increasing depth at Waituna Lagoon is *R. polycarpa*, *M. triphyllum* then *R. megacarpa* (Johnson and Partridge, 1998).

3.3.1 *Ruppia*

Ruppia megacarpa and *polycarpa* (Appendix C.9) have strong ecological value and are integral to the health of Waituna Lagoon (Robertson and Stevens, 2009). Many of the ways *Ruppia* enhance Waituna Lagoon are linked to their functions as macrophytes. In particular, *Ruppia* species are valued as they actively enhance water quality by absorbing nutrients from the water column and reducing sediment resuspension, and provide habitat and food for other species in the lagoon (Stevens and Robertson, 2007). *Ruppia* plants are an important food resource for local and migratory waterfowl.

Ruppia is so vital to the ecological integrity of Waituna Lagoon that the species are often referred to as “keystone species”. However, *Ruppia* has a high biomass in Waituna Lagoon and its influence is density-specific. Therefore it cannot correctly be classified as a keystone species in Waituna Lagoon (Libralato *et al.*, 2006). Nevertheless, as its impact is density specific, the continued dominance of *Ruppia* within Waituna Lagoon is important in maintaining the current ecological values.

Ruppia species are becoming increasingly rare globally due to high levels of nutrient enrichment, and have been lost from many other ecosystems in New Zealand and Australia (e.g. McComb and Davis, 1993). The loss of *Ruppia* beds from Lake Ellesmere (“Te

Waihora”, a similar coastal lake in Canterbury) was associated with rapid ecological deterioration, from which Lake Ellesmere has not recovered (Schallenberg *et al.*, 2010). The increased frequency of opening Waituna Lagoon will impact macrophyte communities as they are inhibited by high salinities (Brock, 1982; Vollebergh and Congdon, 1986).

Ruppia megacarpa and *Ruppia polycarpa* are native to New Zealand and adapted to fresh and brackish water conditions. They are capable of breeding at a salinity of 50 ‰ TDS (parts per thousand total dissolved solvents) though seed production and germination is enhanced by lower salinities (Brock, 1983; Short and Neckles, 1999). High salinities or prolonged exposure due to reduced water levels can be fatal (Brock, 1982; West, 2004).

Despite these similarities the species have different life histories. *R. megacarpa* is a large, hardy perennial which grows in aquatic systems with permanent water, such as Waituna Lagoon (Brock, 1982, 1983). Its breeding method is polycarpic or iteroparous, whereby individuals may breed multiple times, with fewer propagules produced in each event (Brock, 1983). *R. megacarpa* seeds establish a permanent seedbank, lying dormant in the sediment until a decrease in salinity initiates germination (Brock, 1983).

R. polycarpa is a small, weak annual which often grows in ephemeral habitats and may complete its lifecycle in as little as six weeks (Brock, 1982, 1983). It has a monocarpic or semelparous reproductive strategy, whereby individuals reproduce in a single event which results in many propagules (Brock, 1983). *R. polycarpa* reproduces equally well in fresh and salt water (Brock, 1982, 1983).

Myriophyllum triphyllum (Appendix C.6) is the third most dominant macrophyte in Waituna Lagoon. Changes in the relative dominance of these three species were recorded between 1998 and 2009. Studies published in 1998 and 2003 described *R. megacarpa* and *M. triphyllum* as dominating the macrophyte community from 0.7 - 2.0 m depth (Johnson and Partridge, 1998; Thompson and Ryder, 2003). By 2007 this area (including 0.5 - 2.5 m depth) was dominated by *R. megacarpa*, with *M. triphyllum* occurring at low densities in disjunct patches (Stevens and Robertson, 2007; Robertson and Stevens, 2009). Between 2007 and 2009 *R. megacarpa* decreased in abundance, with *M. triphyllum* numbers increasing, and *R. polycarpa* had become the dominant macrophyte in Waituna Lagoon (Robertson and Stevens, 2009). During the same time period the abundance of macroalgae had dramatically increased, decreasing the water quality and smothering *Ruppia*

(Robertson and Stevens, 2009). These rapid changes in vegetation composition may be a response to increasing eutrophication (Robertson and Stevens, 2009).

3.4 Fauna

The wetlands support abundant wildlife, including a range of rare or endangered species (Thompson and Ryder, 2003). International and regional migrant birds can be found in the wetlands, including up to seventeen species from the Northern Hemisphere (Stephenson, 1986). Local avifauna includes New Zealand natives such as *Egretta alba modesta* (white heron; Thompson and Ryder, 2003). Sixteen other species with observed declines have been recorded at the lagoon and wetlands, including three critically endangered species (Thompson and Ryder, 2003). The wetlands are also home to many sub-alpine insects, including over eighty species of moth (Stephenson, 1986).

A range of marine, estuarine and freshwater fish species inhabit the lagoon, many with both freshwater and marine phases (Ridell *et al.*, 1988). The lagoon has long been known for large introduced sea-run *Salmo trutta* (brown trout; Stephenson, 1986), which here co-exist with native *Galaxias* species (kokopu; Ridell *et al.*, 1988). *S. trutta* were first released into Waituna Lagoon in 1900, and by 1918 had established a self-sustaining population (Ridell *et al.*, 1988). Eels are present in large numbers, with the lagoon recognized as an important spawning ground (Ridell *et al.*, 1988). The most prized species in this ecosystem for recreational activities and mahinga kai are eels, ducks, galaxiids and trout.

3.5 Recent degradation

Waituna Lagoon is becoming degraded due to anthropogenic activities. Land use changes in the catchment, primarily the advent and intensification of farming, and artificial management of the opening regime have had a large impact on the health of Waituna Lagoon (Thompson and Ryder, 2003).

Drainage and clearance of native vegetation for farming and grazing of livestock has decreased the size of the wetlands (Thompson and Ryder, 2003). Recently a network of tile-lined drains has been developed to facilitate drainage by bypassing the wetlands, which



Figure 8: Farmland around Waituna Lagoon, showing tile drains (photo: M. Schallenberg, taken in 2008)

previously filtered agricultural runoff before it passed into the lagoon (Fig. 8). This anthropogenic nutrient enrichment is quickly degrading the water quality of Waituna Lagoon (Thompson and Ryder, 2003; Robertson and Stevens, 2009). Levels of nitrate, ammonia, fecal coliforms and enterococci entering the lagoon all exceed nationally acceptable values (Thompson and Ryder, 2003).

In many similar ecosystems worldwide this increased nutrient input has resulted in eutrophication, decreased macrophyte abundance and resuspension of sediments (Schallenberg *et al.*, 2010). This process is evident in Dunedin's Tomahawk Lagoon, a similar coastal lake which rapidly switched to a eutrophic, phytoplankton dominated system after land use changes led to nutrient enrichment (McKinnon and Mitchell, 1994; Thompson and Ryder, 2003). Tomahawk Lagoon still alternates between states of macrophyte and phytoplankton dominance, but in some systems such as Lake Ellesmere this change between states appears to be permanent.

Although Waituna-type lagoons are naturally oligotrophic (Kirk and Lauder, 2000), Waituna Lagoon is currently classified as meso-eutrophic (Schallenberg *et al.*, 2010; based on the classification in Burns *et al.*, 2000). Increased nutrient input to Waituna Lagoon from land use changes has been associated with increased turbidity, phytoplankton and filamentous macroalgae biomass (Environment Southland, 2011). These variables are

threatening macrophyte beds, resulting in further sediment instability and ecological deterioration (Schallenberg and Tyrrell, 2006; Robertson and Stevens, 2009; Environment Southland, 2011).

The barrier which separates Waituna Lagoon from the sea has been artificially breached approximately once a year since 1908, most commonly to benefit agriculture but also for recreational activities (Kirk and Lauder, 2000; Thompson and Ryder, 2003). The opening regime has been fully managed since 1972, with largely unknown effects upon the lagoon. A recent study suggests that breaching the barrier may not have a large impact on farmland drainage (Thompson and Ryder, 2003). Continuing to artificially open the lagoon may be desirable despite this, as there are indications the lagoon is becoming increasingly eutrophic (Robertson and Stevens, 2009) and opening the lagoon flushes the nutrient-rich waters out of the system and into the coastal environment (Thompson and Ryder, 2003).

3.6 Aim and hypotheses

This study was conducted to assist the Department of Conservation with the management, and potentially restoration, of Waituna Lagoon. Therefore the aim of this study was to reconstruct the natural opening regime and *Ruppia* abundance, as these are key components of Waituna Lagoon (Schallenberg and Tyrrell, 2006). With *Ruppia* the focus was on its presence and dominance, rather than its density. This reference condition will assist in setting restoration goals by describing aspects of the lagoon before anthropogenic disturbance, and will help assess the appropriateness of the present regime (Vivian-Smith, 2001; Smol, 2008).

As part of this descriptive study three hypotheses were tested: (1) that under a natural opening regime, environmental variations within Waituna Lagoon were less frequent but more extreme; (2) that *Ruppia* was not present in Waituna Lagoon under a natural opening regime; and (3) that *Ruppia* was not dominant in Waituna Lagoon under a natural opening regime. These hypotheses are interlinked as *Ruppia* is limited by light requirements (Schallenberg and Tyrrell, 2006), and therefore its abundance may be mediated by the opening regime as it regulates water depth. The hypotheses are summarised in a

conceptual model below (Fig. 9). The study also looked at intra-lagoon variation in sediment records, for the benefit of future research.

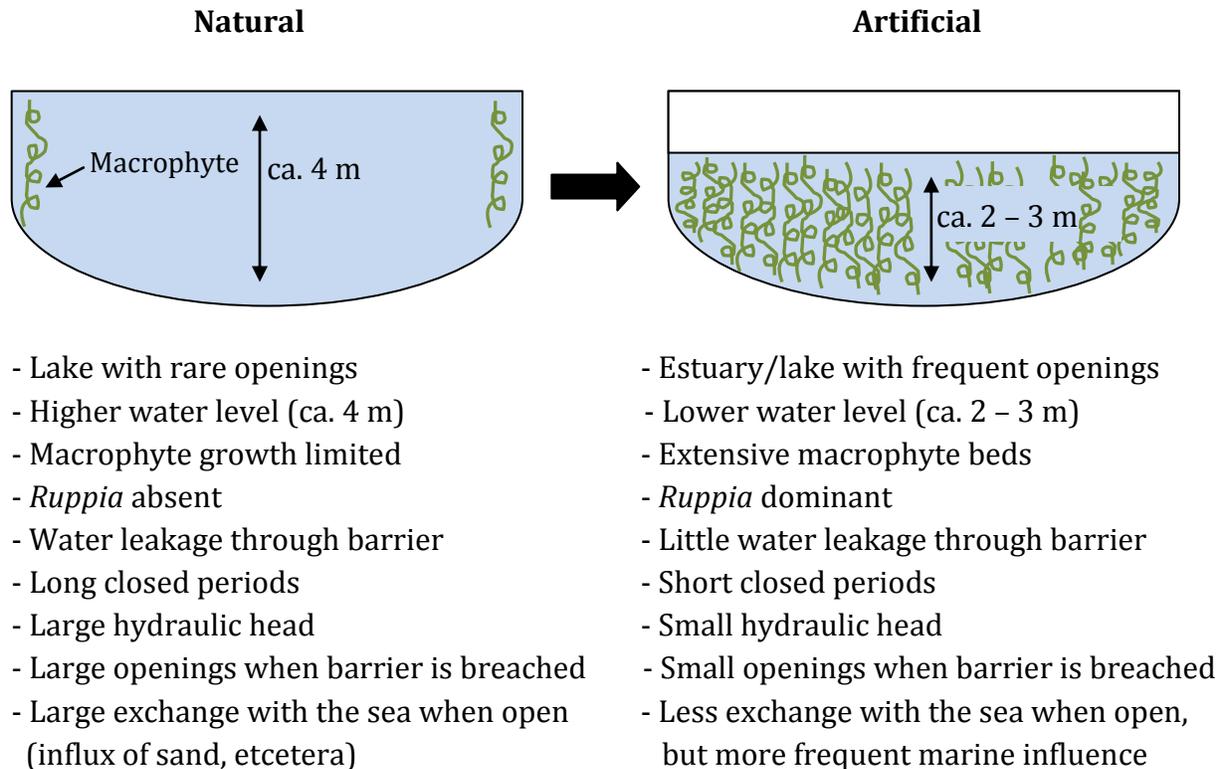


Figure 9: A conceptual model showing the hypothesized natural state of Waituna Lagoon alongside the present conditions under artificial management

The opening regime is currently being artificially managed, with the consent to come under review in 2014. The natural opening regime was not recorded prior to modification, but this information is important for establishing an appropriate regime. Under a natural opening regime Waituna Lagoon was open to the sea less frequently. It is proposed that this enabled it to equilibrate between freshwater and marine phases. This equilibration may be caused by frequent leakage through the barrier bar, which occurs at relatively high water levels and may delay opening (Schallenberg *et al.*, 2010). This would result in a larger hydraulic head when the lagoon opened. It is proposed that this larger hydraulic head resulted in larger openings than are presently achieved (Haines, 2006), and helped the lagoon stay open for longer.

This study seeks to establish whether *Ruppia* was a component of Waituna Lagoon under a natural opening regime. This hypothesis was suggested by a local with a multi-generational connection with Waituna Lagoon, who had been told that *Ruppia* was not present before 1908 when artificial management began. This suggests that *Ruppia* may be invasive in Waituna Lagoon, and has important implications as the Department of Conservation is considering altering the opening regime to enhance ecological aspects of the lagoon, such as *Ruppia* flowering (H. Robertson, pers. comm., 2009). As an alternate hypothesis, it is proposed that *Ruppia* was present but not dominant under the natural opening regime.

4. Methodology

This chapter presents a brief summary of the methods used in the collection and analysis of sediments from Waituna Lagoon. A detailed discussion of the methods and rationale is presented in Appendix A, and their utility in this study is discussed in Appendix D.

There is some repetition between this section and Appendix A. Complete, detailed methods could not be found for many of the proxies tested, and others (such as the methods for charcoal and foraminifera) required modification to suit the sediment from Waituna Lagoon. Appendix A provides detailed instructions on some paleolimnological analyses for humic, peaty sediments. The rationale behind the trialing of alternate methods is included to assist future research.

4.1 Sampling sites and core collection

Sampling was conducted on 15 October 2009, eleven days after the lagoon closed. The water level was still relatively low, averaging 919 mm at the Waghorn Road bridge staff gauge during the week of sampling (Fig. 10) and 932 mm during sampling, 268 mm below normal (Environment Southland, unpubl. data; Fig. 11).

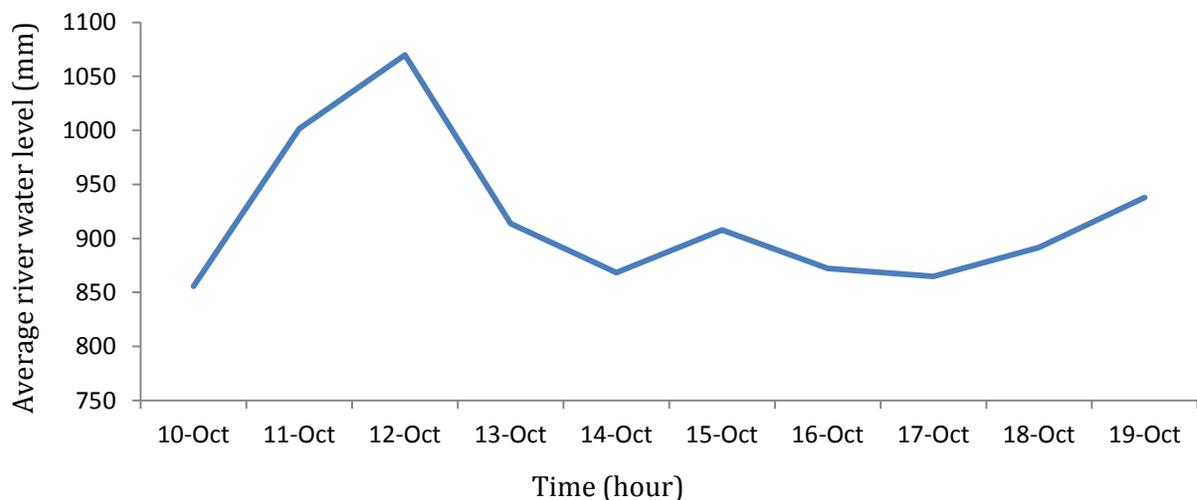


Figure 10: The water level recorded at the Waghorn Road bridge staff gauge during the week of 10 - 19 October, 2009 (data: Environment Southland, unpubl. data)

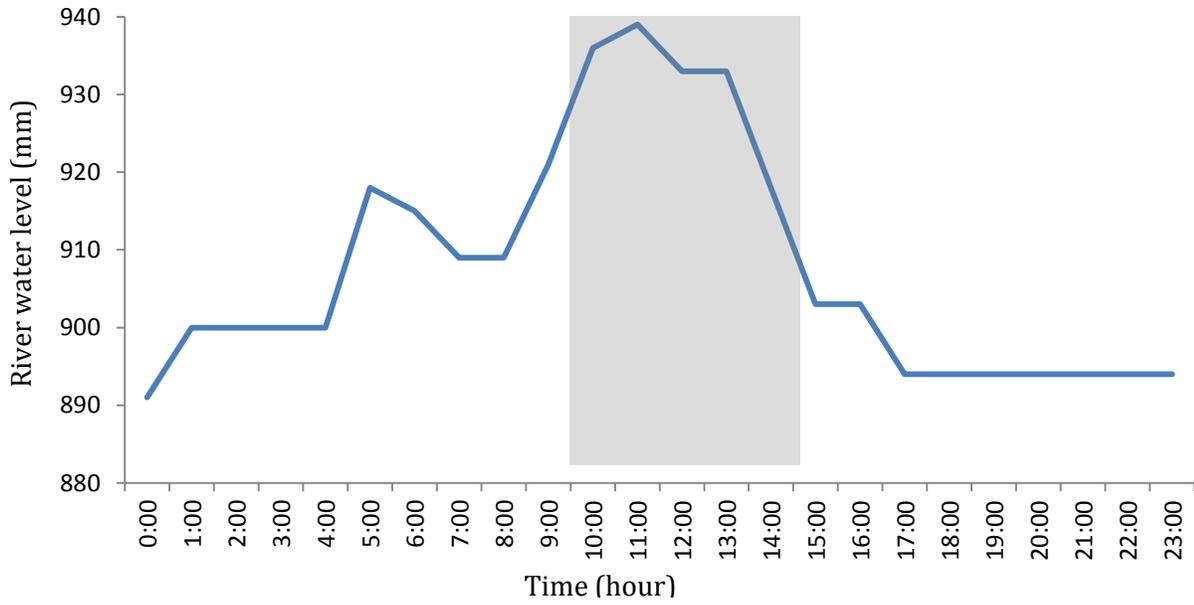


Figure 11: The water level at the Waghorn Road bridge staff gauge on 15 October 2009. Sampling occurred between 1000 and 1400 hours (highlighted), when the water level peaked for the day (data: Environment Southland, unpubl. data)

Two sampling sites were selected using a bathymetric map. One site was in Shand Bay, a sheltered embayment on the lagoons western edge, the other in the deepest area of a deposition basin in the eastern arm, near Hansens Bay (Fig. 12).



Figure 12: Coring locations within Waituna Lagoon, Southland. Areas where the lagoon may breach are indicated by boxes. The lagoon has breached naturally in all three zones. Since 1958 manual breaching has been in the western arm (modified from Google Earth, 2010)

Five sediment cores were collected using PVC drain pipes (inner diameter 70 mm) and a push-coring method whereby the core tubes were driven vertically into the sediment until friction prevented further penetration. The cores were then capped with an airtight fitting and carefully removed vertically from the lake bed. Core shortening and GPS locations were measured prior to extraction. Cores remained upright and were stored at 5°C until they were opened for sectioning and analysis.

Three cores were used as the basis of this study. Core I (Shand Bay; E2169949, N5395140; 130 cm) was the primary core for analysis, as it had the greatest length and the clearest x-ray density stratigraphy. Cores II (Shand Bay; E2169844, N5395165; 83 cm) and III (Eastern arm; E2174845, N5395175; 64 cm) were tested for a limited range of proxies (Table 3) to determine if stratigraphic patterns were similar at different sites in the lagoon.

Table 3: Summary table of the cores collected and analyses carried out on the cores. A dash indicates that the method was not used

Analysis	Core I	Core II	Core III
	Shand Bay	Shand Bay	Eastern arm
X-ray densitometry	Tested	Tested	Tested
Organic and water content	Tested	Tested	Tested
Sediment grain size	Tested	-	Tested
²¹⁰ Pb	Tested	-	-
Electrical resistivity	-	Tested	Tested
Gamma-ray attenuation (bulk density)	-	Tested	Tested
Magnetic susceptibility	-	Tested	Tested
Charcoal	Tested	-	-
Pollen	Tested	-	-
Foraminifera	Tested	-	-
Macrofossils (355 - 3000 µm)	-	-	Tested
Macrofossils (> 3000 µm)	Tested	Tested	Tested

4.2 Sediment extrusion

Sediment was extruded from the core tubes to enable analysis. Core I was extruded by laying the core horizontally and pushing the intact sediment out of the core tube from below onto a half-section of PVC drainpipe. Care was taken not to compress or stretch the core during extrusion. The outer layer of the sediment was removed prior to sectioning the core into 1 cm slices, with care taken to avoid contamination between samples.

Cores II and III were split lengthwise to enable testing on the Geotek Multi-Sensor Core Logger. The plastic tubing was split using an angle grinder and the sediment divided with a thin wire. The blade of the angle grinder did not damage the sediment, and swarf was removed with tweezers. Half of each core was sectioned into 1 cm slices, the other half was archived. For simplicity, the half cores analysed are hereafter referred to as “the core/s”.

4.3 Organic and water content

Analyses of sedimentary organic and water content are completed in most paleolimnological studies (e.g. Pèlachs *et al.*, 2011) and was used to compare cores and establish the opening regime. Organic and water content was measured in all cores through the standard loss on ignition procedure (Håkanson and Jansson, 1983). Immediately after opening the cores 5 g of sediment was removed at 1 cm intervals. These samples were weighed, dried at 60°C for 48 hours then reweighed. Dry samples were then ashed in a muffle furnace for 24 hours at 500°C before being reweighed. Water content could not be measured on Core II as it drained in storage.

4.4 Sediment grain size

Sediment grain size is commonly analysed to infer changes in the sedimentation rate (Cadmus, 2004) and hydrology (Yang *et al.*, 2008). It was assessed in Cores I and III at 1 cm intervals to compare sites and reconstruct the historic opening regime. Sediment smaller than 3 mm was assessed using the Horiba Laser Scattering Particle Size Distribution Analyser LA-950V2 with the software Horiba NexGen LA-950 for Windows. A small quantity of each sample was mixed thoroughly with milli-Q water to break down aggregates

of grains. This slurry was pipetted into the Analyser, which calculated the grain size distribution from 0.001 to 3000 μm .

Oversized particles were removed via wet sieving. The entirety of each sample was weighed and wet sieved through a 3000 μm mesh then the gravel was dried, counted and weighed. To avoid cross-contamination this proxy completed last, while extracting macrofossils. The remaining sediment from all other proxies was wet sieved upon their completion to ensure all gravel was represented in the data.

4.5 ^{210}Pb

Analyses of ^{210}Pb concentrations are commonly used to date sediments up to 150 years old (Saulnier-Talbot *et al.*, 2009). Nineteen samples from Core I were analysed for ^{210}Pb by MyCore Ltd (Chalk River, Canada) by analyzing ^{210}Po , the granddaughter of ^{210}Pb . One gram of dry sediment from each sample was spiked with ^{209}Po using acidification and heat treatment. Po isotopes were electroplated onto silver discs and ^{210}Po measured using isotope dilution alpha spectrometry, the sediment weight and the quantity of ^{209}Po initially added to the sample. This was used to construct the ^{210}Pb activity.

4.6 Geotek multi-sensor core logger

Cores II and III were analysed using the Geotek Multi-Sensor Core Logger, with MSCL software version 7.95.3 and GeoScan digital imaging software version 3.1.

Before the cores were opened electrical resistivity, gamma-ray attenuation (bulk density) and magnetic susceptibility were analysed. Cores were split lengthwise and the sediments allowed to equilibrate to lab temperature over 72 hours. A high resolution colour image of the split cores was created on the Analyser, which also measured the gamma-ray attenuation, magnetic susceptibility and average reflectance.

4.7 Charcoal

Charcoal was analysed as an indicator of fire disturbance, to complement the pollen analysis. Seventeen dry samples of 0.2 g were rehydrated then bleached at 50°C using 6%

hydrogen peroxide (Rhodes, 1998). Dark organic leachate was removed by filtering the samples. Samples were dried and weighed again. Charcoal particles were counted under a dissecting microscope. A grid was used to ensure particles were only counted once.

4.8 Pollen

Pollen was analysed in Core I using a protocol described in Fig. 13 to describe changes in key taxa and verify the ^{210}Pb chronology. Species which are indicative of land-use changes (section 2.3.1) or important for answering the hypotheses (section 3.6) were identified, with other species counted by not identified due to time constraints. A detailed rationale of how indicator species were selected may be found in Appendix A.7.8.

Dacrycarpus dacrydioides (kahikatea), *Dacrydium cupressinum* (rimu), *Pinus radiata* (Monterey pine) and *Weinmannia racemosa* (kāmahi) were identified to assist with dating. *Leptospermum scoparium* (mānuka) and *Pteridium esculentum* (bracken fern) were identified as indicators of terrestrial disturbance and to assist with dating. *Myriophyllum triphyllum* (water milfoil), *Ruppia megacarpa* (large-fruit tassel) and *Ruppia polycarpa* (horse's mane weed) were identified as they are currently the most dominant macrophytes in Waituna Lagoon (Robertson and Stevens, 2009) and to address hypotheses two and three. *Ruppia* was identified to genera as the pollen of both species are extremely similar and the distinction was not considered important.

Guides used for identification include Erdtman (1952, 1969), Moore *et al.* (1991) and Raine *et al.* (2005). A tablet of *Lycopodium* spores (Lund University) was added to each pollen sample to determine the pollen extraction efficiency and to assist with the determination of pollen counts.

4.9 Foraminifera

Foraminifera are often used as paleoenvironmental indicators (e.g. Fiorini *et al.*, 2010). They were analysed to indicate fluctuations in salinity as a component of the opening regime. Foraminifera were extracted from Core I using a targeted method and from Core III with other macrofossils (section 4.10).

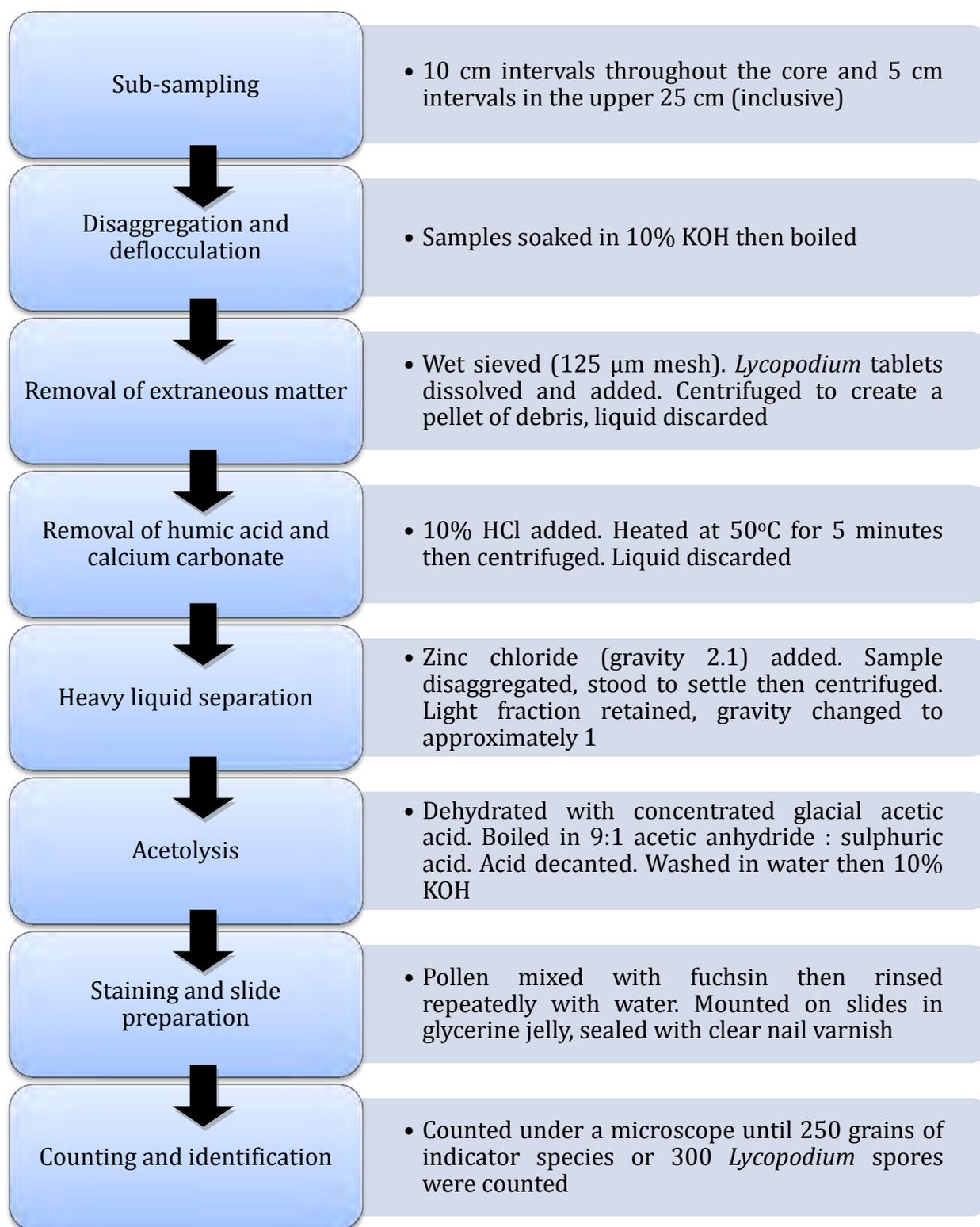


Figure 13: Summary of the pollen methodology used in this study. Method developed using Fægri and Iversen (1975), Moore and Webb (1978), Jones and Cundill (1978), Vandergoes (2000) and Cadmus (2004)

Dry 20 g samples were taken at 1 cm intervals from the deep sandy portions of Core I (101 – 130 cm; Hayward *et al.*, 2007). After testing for calcareous material using HCl and examination for foraminifera under a dissecting microscope, samples were wet sieved through a 63 μm metal sedimentology sieve. Samples were checked for foraminifera again, then dry sieved through a 500 μm mesh to remove coarse material. Foraminifera were removed from the fine sample by suspending the sample in chloroform, and pouring the lighter portion through filter paper. Once dry, filter papers were analysed for foraminifera under a dissecting microscope.

4.10 Macrofossils

Sediment from 130– 80 cm of Core I and all of Core III were examined for macrofossils of 355 - 3000 μm . Samples were weighed then wet sieved through nested metal sedimentology sieves of 355 and 3000 μm . In Core I the focus was on finding material suitable for ^{14}C dating. In Core III all macrofossils of 355 - 3000 μm diameter were counted and identified. This analysis was conducted as macrofossils were found in Core III during a preliminary microscopic analysis of the surficial sample. Unfortunately insufficient sediment was available to complete this analysis for both sites.

To extract *Ruppia* seeds and material suitable for ^{14}C dating all cores were wet sieved for macrofossils larger than 3000 μm . Macrofossils were extracted, counted and identified.

4.11 Data processing and analysis

Charcoal and pollen data were standardised. Charcoal density was calculated as particles per mg of dry sediment. The number of particles was used in preference to the weight, to make the data more comparable with other measurements of sediment grain size. The Horiba Analyser calculated the sediment grain size based upon the number of particles in each size class. For each indicator species the pollen count was standardised as the percentage of the total pollen sum, excluding broken grains and *Lycopodium* spores.

Microsoft Excel version 14.0.5128.500 (2010) was used for data processing, statistical analyses and the creation of graphs. The statistical analyses performed were linear

regressions, a chi-square test, Analyses of Variance (ANOVAs) and a Principal Components Analysis (PCA). For all analyses values of $\alpha < 0.05$ were considered significant.

Linear regressions were calculated to explain the significance of correlations between variables, and scatter-graphs created to give R^2 values.

Chi-square is a nonparametric test which calculates the probability that the observed trends could have occurred by chance (Salkind, 2008). A one-sample chi-square test was used to compare the results of the methods used to establish the opening regime.

An Analysis of Variance (ANOVA) is an analysis which assesses the difference between sets of data by comparing the variance within and between groups (Salkind, 2008). One-way ANOVAs were used to determine whether the variability in factors used to establish the opening regime was different before and after 50 cm. ANOVAs were calculated separately for the organic content and sand in Core I.

A Principal Components Analysis (PCA) was conducted using Canoco for Windows software version 4.55 and CanoDraw for Windows version 4.14. PCA is an unconstrained multivariate analysis which creates axes by a least-squares regression (Samman, 2000). The percentage of variance encompassed by each axis is explained by the eigenvalues (Samman, 2000). Samples are placed along the axes according to their values, with similar sites clustering (Samman, 2000).

A Principal Components Analysis (PCA) was conducted to determine the environmental correlates of *Ruppia* and *M. triphyllum* pollen abundance. A PCA was constructed using data on sediment grain size, water content and organic content, from the 15 samples for which pollen data was available. Silt was excluded as the grain size variables were interdependent and including both sand and silt masked all other variation. The pollen correlations for *Ruppia* and *Myriophyllum triphyllum* were coded as supplementary variables. They were plotted over the PCA of the sediment variables using a centred correlation matrix.

5. Results

This chapter presents select results, with a focus on presenting data that addressed the hypotheses. Hypotheses two and three were combined as they both pertain to *Ruppia*. This chapter also includes a sediment chronology as this is necessary for interpreting the results and applying them to a pre-/ post-European framework, and a limited analysis of intra-lagoon variation to assist future research. Additional results are presented in Appendix B.

Core I was selected as the primary core for this research as it had the greatest length and clearest x-ray density stratigraphy. Therefore this chapter focuses upon results from Cores I (130 cm length) and II (83 cm), replicate cores from Shand Bay. Cross-core comparisons using linear regression showed that sediment characteristics in Cores I and II were strongly positively correlated (e.g. organic content $R^2 = 0.648$, $P < 0.001$). Core III from the Eastern arm was not used extensively to answer the hypotheses due to its short length (64 cm).

5.1 Sediment chronology

Through linking the sediment depth profile with measurable time, sediment chronologies enable researchers to distinguish between natural and anthropogenic variation. This is central to the present study as it aims to describe the natural conditions of Waituna Lagoon. Analyses of ^{210}Pb , charcoal and pollen were completed in Core I to construct the sediment chronology.

Unfortunately, there was insufficient ^{210}Pb in the samples to accurately date the sediments (Appendix B.2). Pollen grains from *Dacrycarpus dacrydioides*, *Dacrydium cupressinum*, *Leptospermum scoparium*, *Pinus radiata*, *Pteridium esculentum* and *Weinmannia racemosa* were identified and charcoal fragments counted to assist dating (Figs. 14 and 15). The data is presented as area graphs as samples were not equidistant. The deepest pollen from *P. radiata* was found at 50 cm depth (Fig. 15). Most species and charcoal have markedly different abundances before and after 50 cm depth, with a zone from 60 - 30 cm where most changes occurred. This zone is attributed to the change from a natural pre-European state to an anthropogenically modified system, with sediment above 50 cm deposited after this transition. On the figures a line marks post-transition sediment.

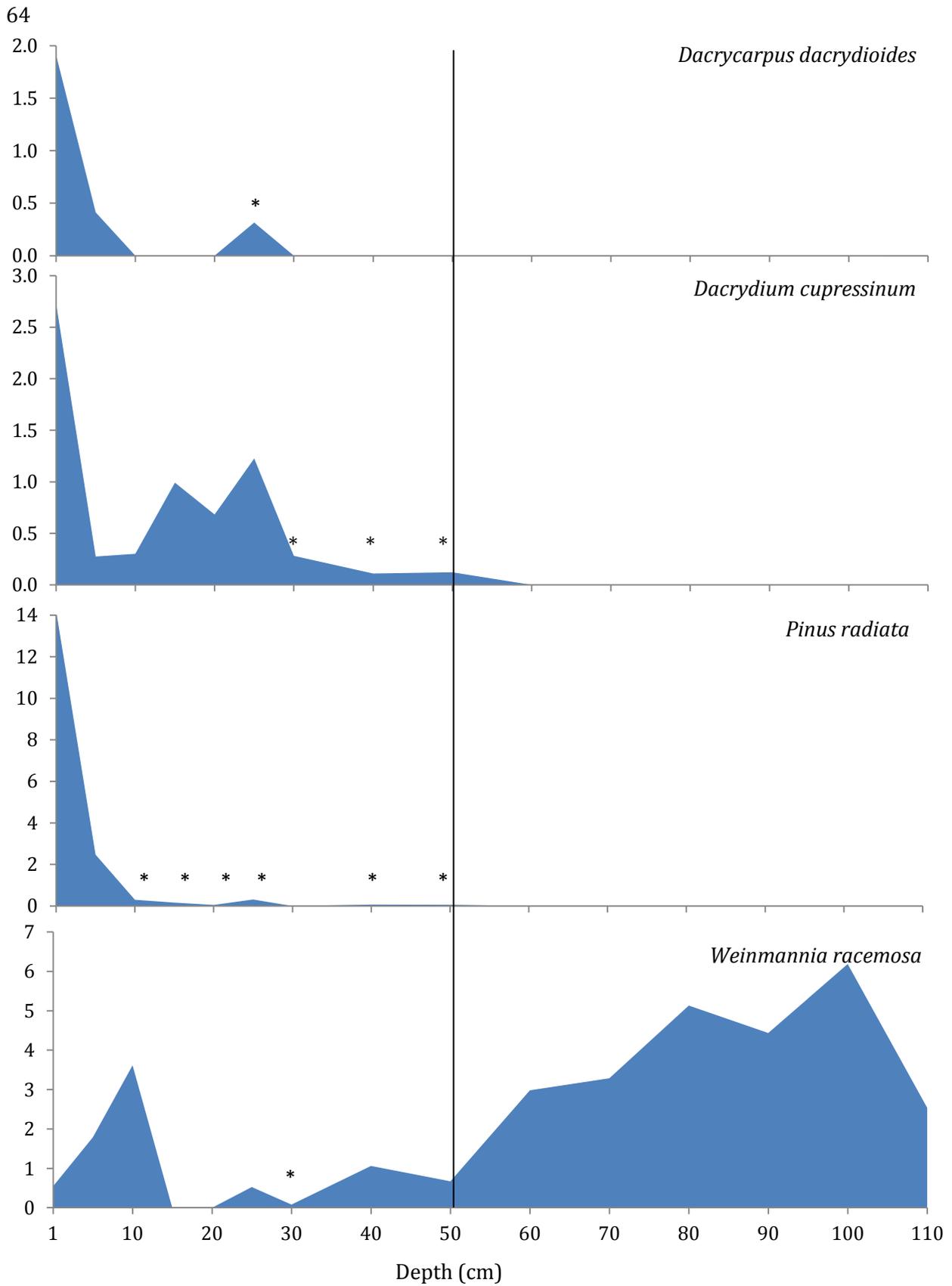


Figure 14: The relative abundance of pollen from four indicator species in Core I (Shand Bay) taken at Waituna Lagoon. Pollen values are on the y-axes as percentages of the total pollen counts. Asterisks indicate a pollen abundance of 0.01 – 0.3%. $N = 15$

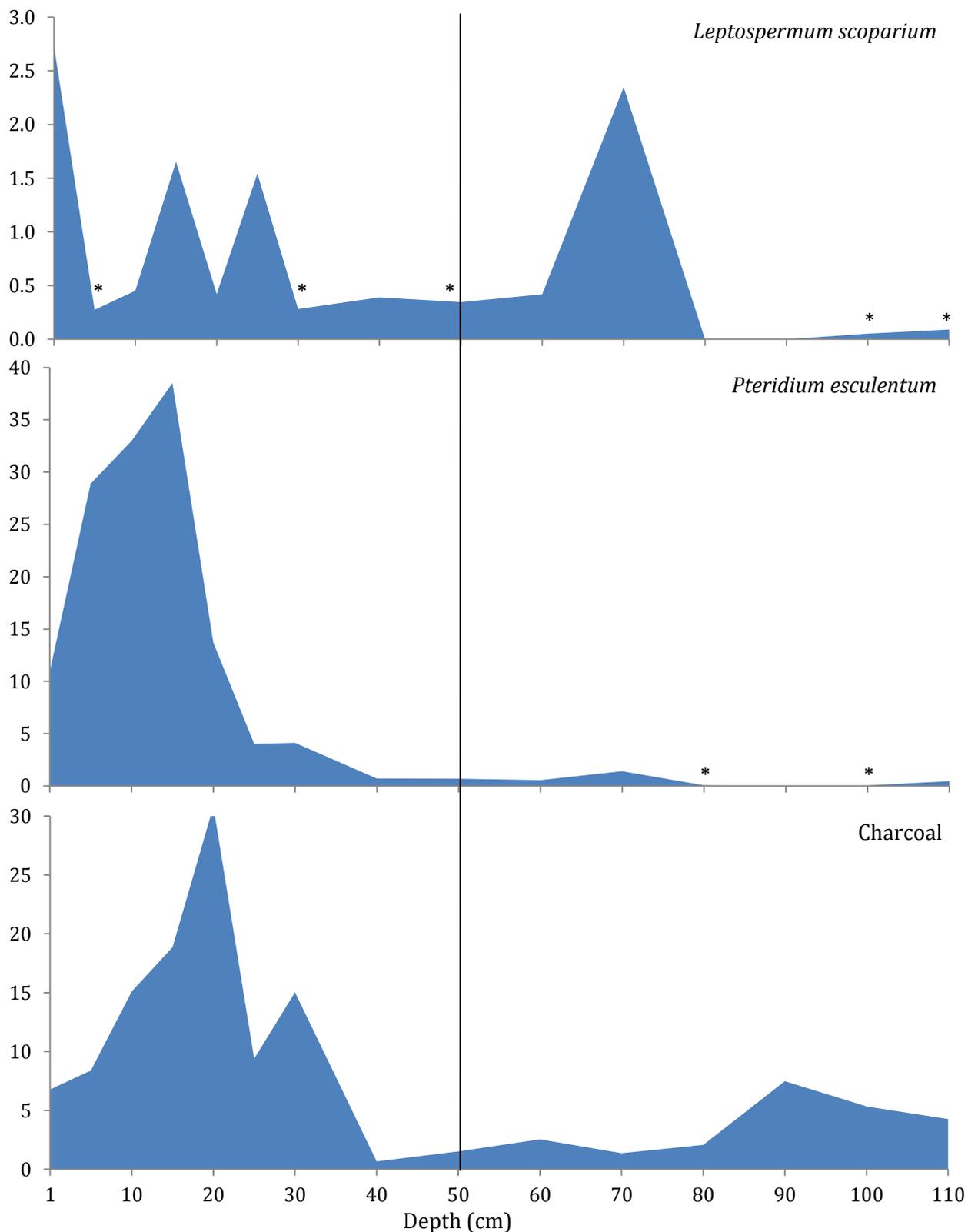


Figure 15: The abundance of pollen from three indicator species, and the charcoal density in Core I (Shand Bay), Waituna Lagoon. Pollen values are the percentages of the total pollen counts. Charcoal values are expressed as the density (number of particles / mg dry sediment). Asterisks indicate a pollen abundance of 0.01 - 0.3%. $N = 15$

W. racemosa was most abundant before 50 cm depth. All other species and charcoal comprised a higher percentage of the pollen record after 50 cm. *L. scoparium* is the only species which comprised a similar percentage of the pollen record before and after 50 cm depth.

Pteridium esculentum and charcoal were most abundant from 30 - 5 cm depth (Fig. 15). There is a significant positive correlation between these variables ($R^2 = 0.327$, $P = 0.014$; Fig. 16), although there was not a significant correlation between charcoal density and the total pollen count. There is a clustering of values against the x-axis (Fig. 16) as from 110 - 40 cm depth *P. esculentum* comprised 0 - 1.4% of the total pollen count.

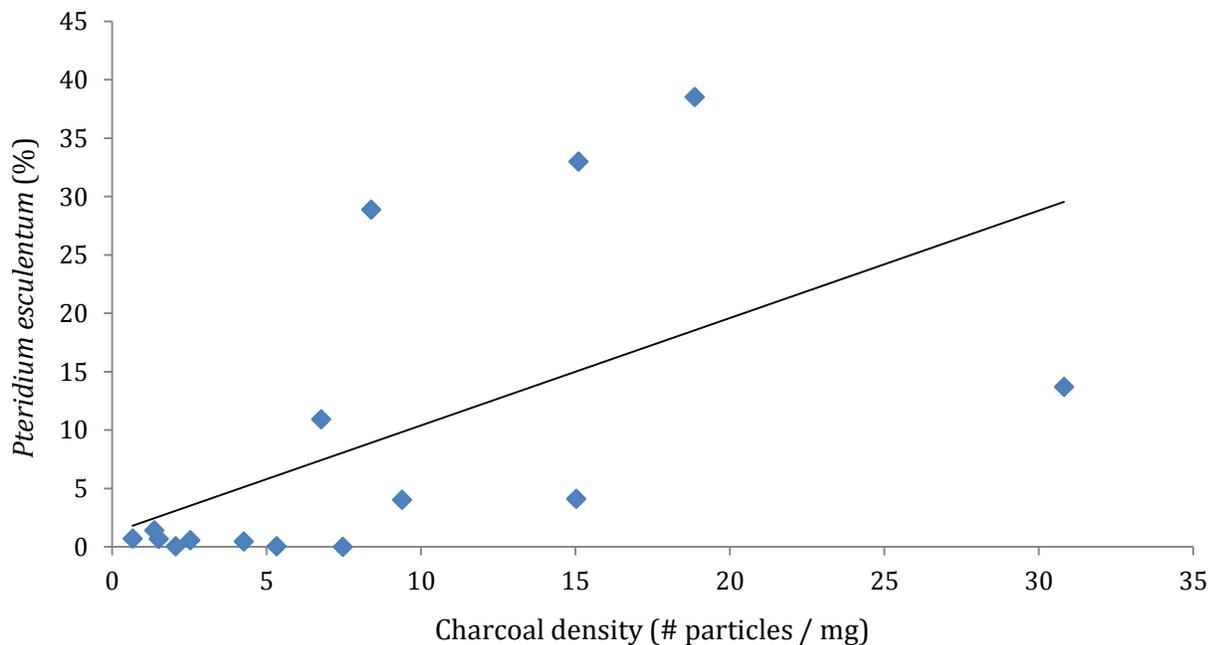


Figure 16: The correlation between *Pteridium esculentum* and charcoal density in Core I (Shand Bay), Waituna Lagoon. *P. esculentum* is expressed as the percentage of the total pollen count. $N = 15$

It is inferred that in Core I (Shand Bay) 50 cm depth is correlated with 1900 AD \pm 10 years. This inference is based upon the pollen and charcoal data, primarily the appearance of *P. radiata* at 50 cm depth. It is used in testing the hypotheses throughout this chapter and further discussed in section 6.1.2.

5.2 Hypothesis one: Opening regime

The first hypothesis of this study was that under a natural opening regime, environmental variations within Waituna Lagoon were less frequent but more extreme. The key variables used to reconstruct the opening regime were the percentages of organic material, silt and sand in the sediment. Organic material and silt were used as indicators of periods when the lagoon was closed. When closed organic material and fine sediment would have accumulated in the lakebed (Spooner and Maher, 2005). Organic material and silt were significantly positively correlated in Shand Bay (Core I; Fig. 17; Table 4).

When the lagoon was open the wave action would have prolonged suspension of organic material and silt. Due to seaward exchange less organic material would have been deposited. Sand would have been transported into the lagoon then deposited (McLean *et al.*, 2003), forming a greater percentage of the sediment than silt. Therefore sand was the primary indicator of open phases, with high levels of sand and low levels of organic material and silt indicating the lagoon was open. Sand was significantly negatively correlated with organic material and silt in Shand Bay (Core I; Figs. 18 and 19; Table 4).

These trends were also observed in the Eastern arm of the lagoon (Core III), though not all trends were significant (Table 4). Due to the greater length of Core I (130 cm, versus 64 cm for Core III) it was used for the reconstruction of the opening regime.

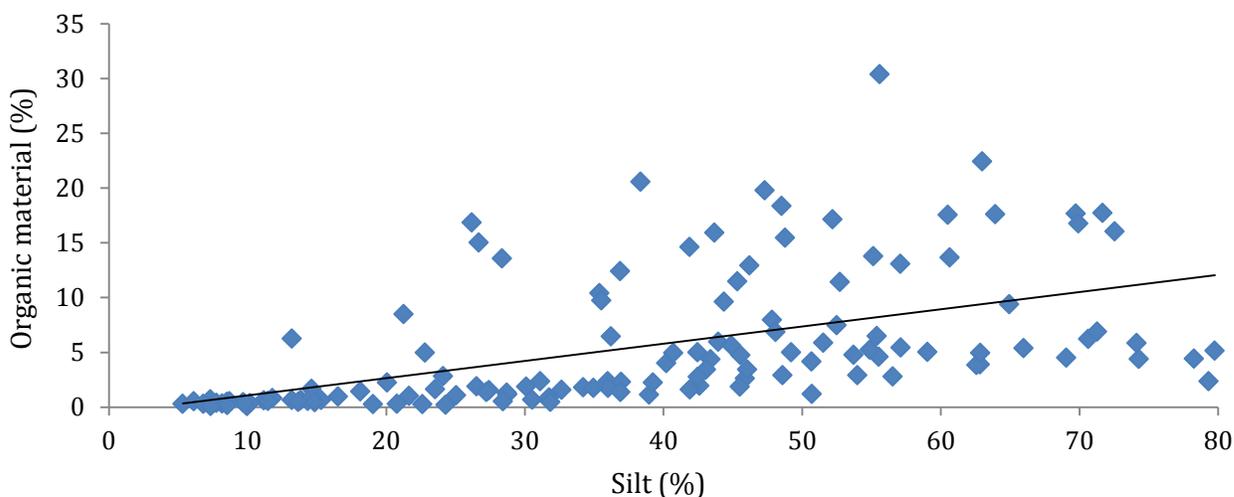


Figure 17: The correlation between the percentages of silt and organic material in Core I (Shand Bay), Waituna Lagoon. $N = 130$

Table 4: Correlations between indicators of the opening regime at Waituna Lagoon using all cores. All variables were analysed as percentages of dry sediment, with “organic” an abbreviation for “organic material”. “ns” indicates the P value was not significant at $\alpha = 0.05$

Variable	Shand Bay (Cores I)			Eastern arm (Core III)		
	R^2 value	P value	Direction	R^2 value	P value	Direction
Sand vs organic	0.241	< 0.001	Negative	0.040	ns	Negative
Sand vs silt	0.727	< 0.001	Negative	0.799	< 0.001	Negative
Organic vs silt	0.263	< 0.001	Positive	0.106	0.008	Positive

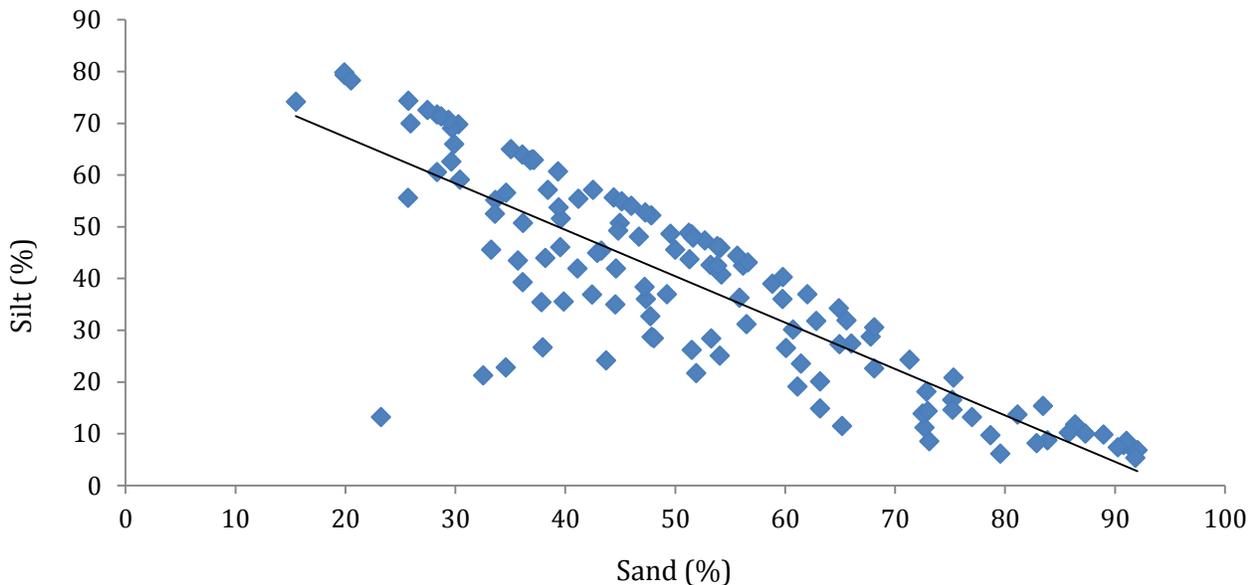


Figure 18: Correlation between the percentages of sand and silt in Core I (Shand Bay), Waituna Lagoon. $N = 130$

There was a significant negative relationship between the percentages of silt and sand in Core I (Fig. 18). This was analysed as sand and silt were indicators that the lagoon was open and closed, respectively. However these variables are not interdependent. To make the results more informative the sediment grain size data was categorised into the percentages of clay, silt, sand and fine gravel. Therefore the percentage of silt directly affects the percentage of sand, and vice versa. Overall the sediment in Core I was 0.15% clay, 38.42% silt, 52.29% sand and 9.14% fine gravel. As these variables are interdependent organic

material and sand were the primary variables for reconstructing the opening regime, with the silt further describing conditions when the lagoon was open.

When the percentage of sand in Core I was high (ca. 58 – 92%) the percentage of organic material was low (0.1 - 2.2%; Fig. 19). This was most pronounced from 130 – 40 cm depth (Fig. 20). When the sand content was less than 60% the quantity of organic material was highly variable (0.5 – 30.4%; Fig. 19). Changes from periods of high sand content to periods of high organic material were gradual, but changes in the opposite direction were sudden (Fig. 20). The exception to this trend was recorded at 66 - 63 cm depth with a sudden change in the relative percentages which was quickly reversed.

The relative abundance of sand and organic material was used to reconstruct the opening regime, using two methods. Both methods involved visually separating graphical representations of the data into three zones: open, closed and transitional. Method one was based on Figure 19 and was relatively objective as the depths of samples were masked. The open zone had < 3% organic material and > 58% sand, and the closed zone > 3% organic material and < 58% sand. All other samples were classified as transitional though some may have been deposited during stable open or closed phases.

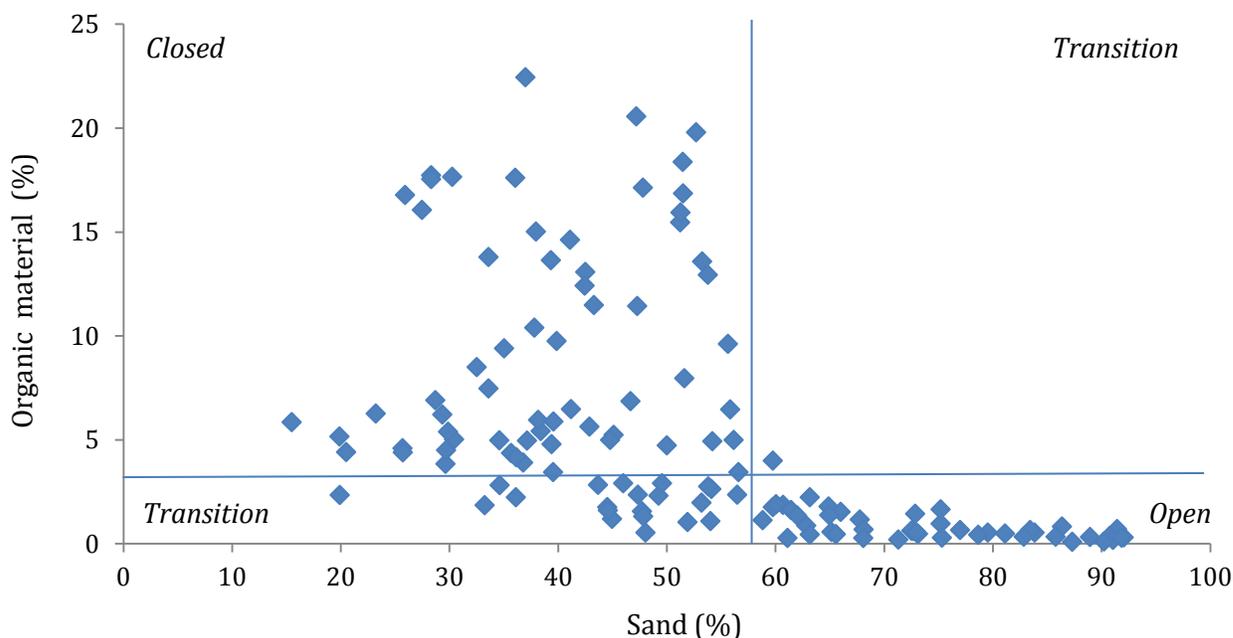


Figure 19: Correlation between the percentages of sand and organic material in Core I (Shand Bay), Waituna Lagoon. The vertical and horizontal lines were used to reconstruct the opening regime. $N = 130$

Method two was based on the same principles but used Fig. 20 (see caption for methodology). The data from 39 - 6 cm was classified as “frequent openings” as it was markedly different to previous open, closed or transitional phases. To minimise bias the data from method one was not compared with depth until after method two was complete.

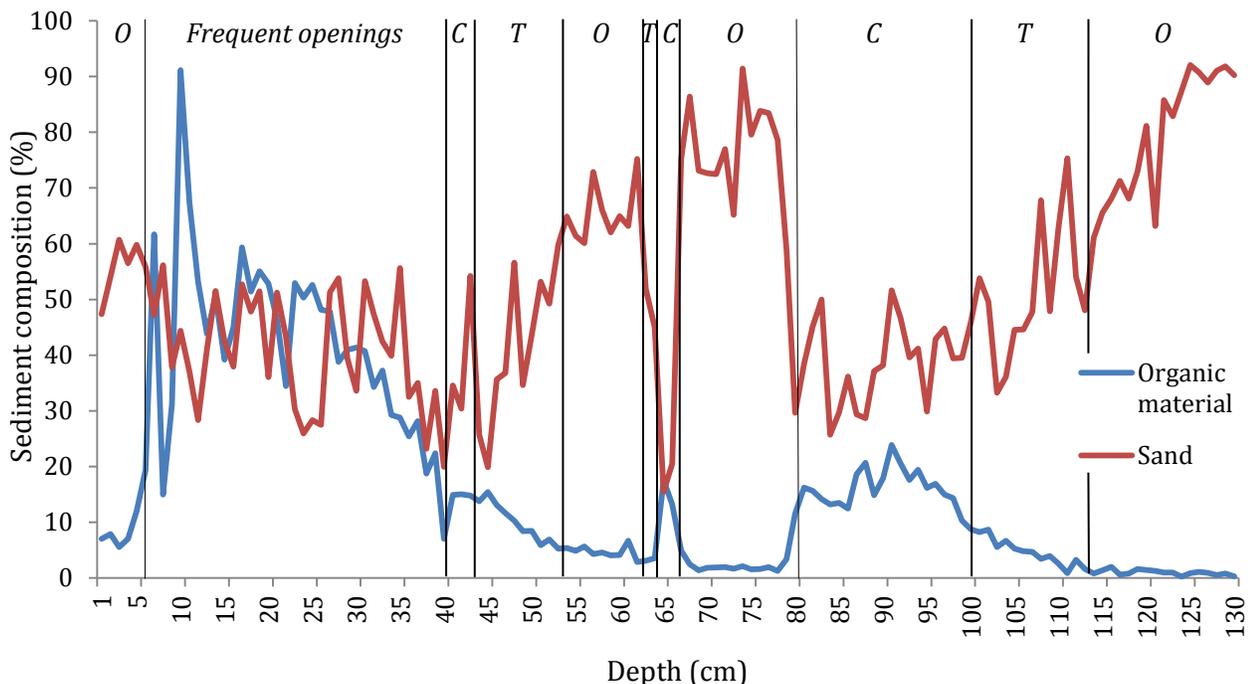


Figure 20: The percentages of sand and organic material with depth in Core I (Shand Bay), giving the historic opening regime of Waituna Lagoon. The organic material values were multiplied by three to clearly display the observed trends. The zones are: relatively high sand and low organic content = open (“O”), relatively low sand and high organic content = closed (“C”), zones where the distinction was less clear = transitional (“T”). $N = 130$

Both methods used to reconstruct the historic opening regime at Waituna Lagoon produced very similar results (Table 5). The percentage of correspondence between these methods was calculated for samples from 130 – 40 cm, as method two could not often differentiate between states from 39 – 1 cm. The methods attributed 82 of these samples to the same state (90.1%), and 9 samples to different states (9.9%). Based upon a one-sample chi-square test the results of these methods are significantly similar ($X^2 = 29.28$, $DF = 1$, $P < 0.01$).

There was no overlap between open and closed periods between methods. Method one classified some samples from 113 – 109 and 5 – 1 cm depth as transitional as the organic content was below the threshold for the open zone. Method two classified the majority of these as open as there was a high percentage of sand and low percentage of organic

material. Method one also classified samples from 39 – 6 cm depth as closed because the percentage of organic material was high. From 40 – 1 cm it was 5.1 times higher than the background rate (130 – 40 cm). Unlike the deeper 90 cm of sediment retrieved there was no clear distinction between phases of high organic material or sand during this zone. Therefore method two classified this zone as a period of frequent openings.

Table 5: The historical opening regime of Waituna Lagoon as reconstructed using two methods based upon the sand and organic content of the sediment

Method one		Method two	
Depth (cm)	Classification	Depth (cm)	Classification
1 – 2	Transition	1 – 5	Open
3	Open		
4 – 5	Transition		
6 – 39	Closed	6 – 39	Frequent openings
40	Transition	40 – 43	Closed
41 – 48	Closed	44 – 52	Transition
49 – 52	Transition		
53 – 62	Open	53 – 62	Open
63 – 64	Transition	63 – 64	Transition
65 – 66	Closed	65 – 66	Closed
67 – 79	Open	67 – 79	Open
80 – 99	Closed	80 – 99	Closed
100 – 107	Transition	100 – 113	Transition
108	Open		
109	Transition		
110 – 111	Open		
112 – 113	Transition		
114 – 130	Open	114 – 130	Open

The main difference between the methods was the increased sensitivity of method one, as samples just below the appropriate thresholds were classified as transitional. Based upon an interpretation of the transitional samples from method one and the chi-squared

analysis, the zones established using method two (Fig. 20) are accepted as the historic opening regime of Waituna Lagoon.

Supporting data comes from macrofossil analyses. The extraction of foraminifera was completed for Core I from 130 – 100 cm depth. Five calcareous foraminifera were found, all at 105 cm depth which corresponds to a period of decreasing sand and increasing organic material. In Core III (Eastern arm) the brackish water foraminifer *Ammonia beccarii* was negatively correlated with the percentage of organic material ($R^2 = 0.101$; $P = 0.010$).

The levels of organic material and sand did not display clear trends for reconstructing the opening regime using Core III from the Eastern arm (Figs. 21 and 22).

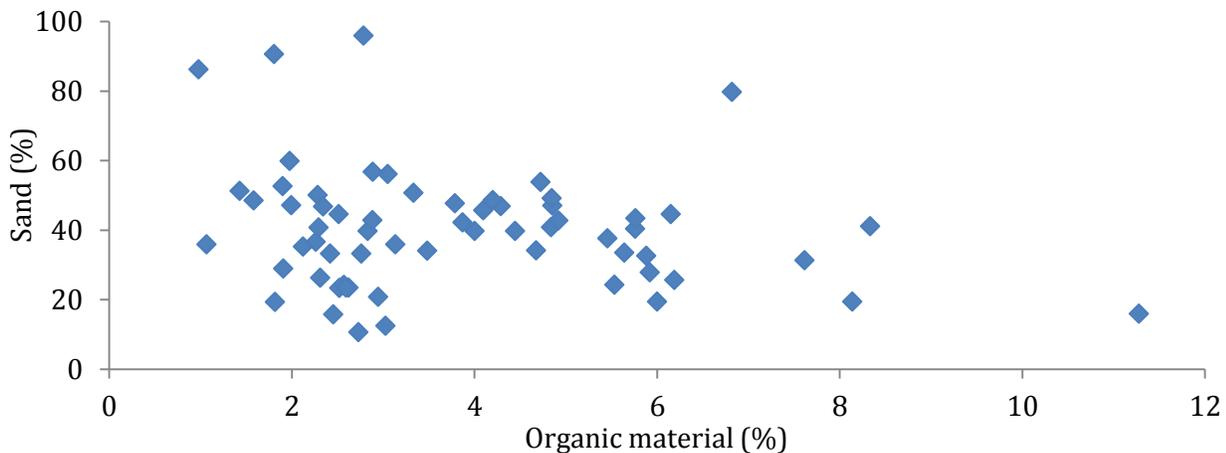


Figure 21: Correlation between the percentages of sand and organic material in Core III (Eastern arm), Waituna Lagoon. $N = 64$

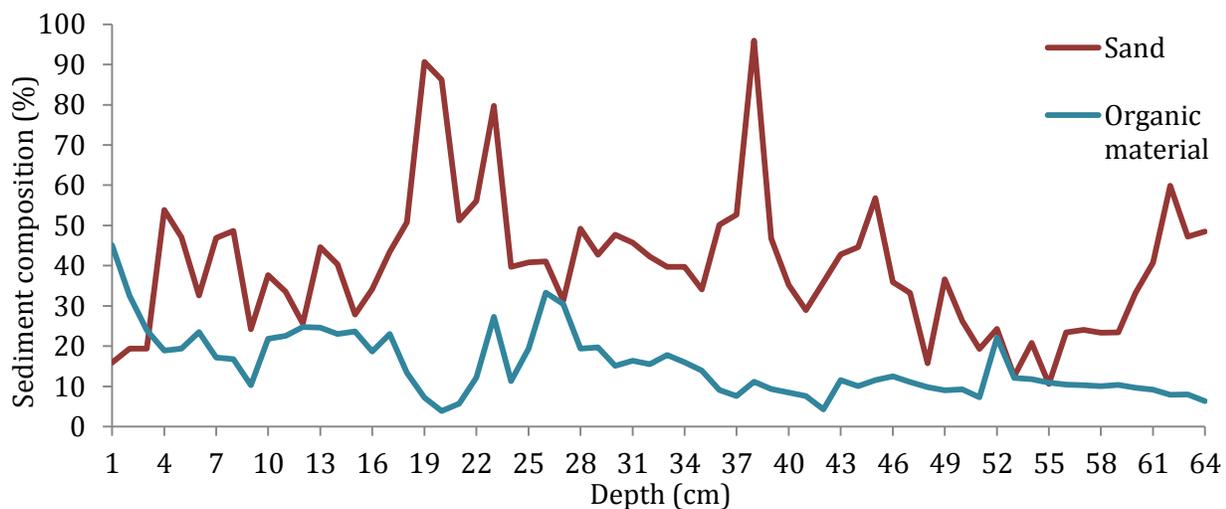


Figure 22: The percentages of sand and organic material with depth in Core III (Eastern arm), Waituna Lagoon. The organic material values were multiplied by three to clearly display the observed trends. $N = 64$

As part of analysing the frequency of variation within Waituna Lagoon under natural and artificial opening regimes the variability in the organic and sand content was tested. A running average of the standard deviation was calculated for every 10 cm of sediment in Core I (Shand Bay; Fig. 23), and one-way ANOVAs were calculated for the percentages of organic material and sand, comparing the variability between 130 – 50 and 49 – 0 cm depth.

The variability of the organic content and sand was significantly different under natural and artificial opening regimes (organic content $F = 117.2$, $P < 0.001$; sand $F = 31.3$, $P < 0.001$). The organic content was most variable from 10 – 0 cm depth and less variable under a natural opening regime (Fig. 23). The percentage of sand in the sediment was most variable from 70 – 60 cm, due to an event at 66 – 63 cm depth. With the exception of this event there did not appear to be a large change in the level of natural variation below 50 cm depth (Fig. 23).

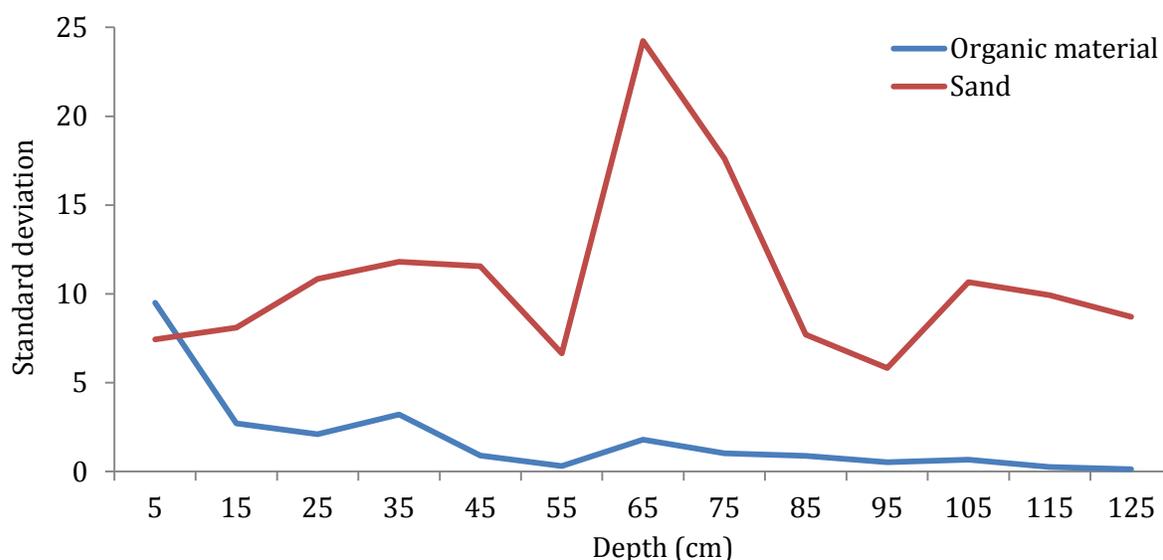


Figure 23: The running standard deviation for the percentages of sand and organic material in Core I (Shand Bay), Waituna Lagoon; calculated at 10 cm intervals. $N = 130$

Waituna Lagoon has fluctuated between zones with high percentages of organic material and silt, and zones with low percentages of organic material and high percentages of sand. Deeper than 40 cm these zones were highly pronounced. In the upper 40 cm there was an infrequent distinction between zones and the percentage of organic material was much higher than the background rate. These changes may be attributed to changes to the opening regime, which may also have affected *Ruppia*.

5.3 Hypotheses two and three: *Ruppia*

Hypotheses two and three are alternate hypotheses about the historic abundance of *Ruppia* in Waituna Lagoon. Hypothesis two is that *Ruppia* was not present in Waituna Lagoon under a natural opening regime. Hypothesis three is that *Ruppia* was not dominant in Waituna Lagoon under a natural opening regime. This section focuses upon these hypotheses, including an analysis of the relative dominance of *Ruppia* and *Myriophyllum triphyllum*, the dominant macrophyte taxa in Waituna Lagoon.

Ruppia pollen was analysed in Core I (Shand Bay). The deepest *Ruppia* pollen grains extracted were at 100 cm depth (Fig. 24).

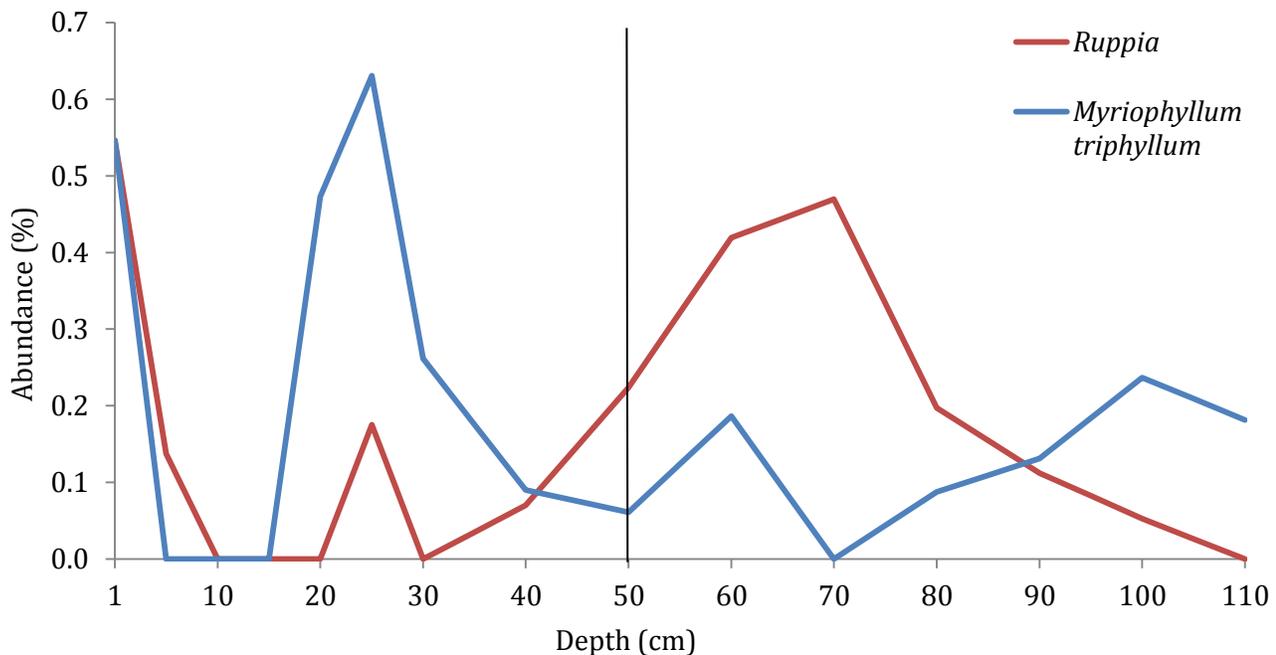


Figure 24: The abundance of *Ruppia* and *Myriophyllum triphyllum* with depth in Core I (Shand Bay), Waituna Lagoon. The abundance is expressed as the percentage of the total pollen count. $N = 15$

Ruppia pollen was more abundant below 50 cm, comprising an average of 0.21% of the total pollen count from 100 – 60 cm and 0.13% from 50 – 0 cm depth. This correlation between *Ruppia* and depth was not significant. The percentage of *Ruppia* in the surficial sample was slightly higher than the highest observed value before 50 cm depth (Fig. 24). The surficial sample was the only one in which *Ruppia* and *M. triphyllum* were abundant at the same time.

Regression analyses comparing *Ruppia* and *M. triphyllum* with sediment characteristics in Core I are presented in Table 6. High levels of organic material and silt are associated with the lagoon being closed and high levels of sand with it being open (section 5.2). These results suggest that *Ruppia* was more abundant when the lagoon was open (Table 6). *M. triphyllum* was weakly correlated with indicators of the lagoon being closed, but was not significantly correlated with any of the variables tested. This may be because it was most abundant in the upper 50 cm when sediment characteristics were more variable.

Table 6: Correlations between the pollen of *Ruppia* and *Myriophyllum triphyllum* and sediment variables from Core I (Shand Bay), Waituna Lagoon. “ns” indicates the *P* value was not significant at $\alpha = 0.05$

Variable	<i>Ruppia</i>			<i>Myriophyllum triphyllum</i>		
	<i>R</i> ² value	<i>P</i> value	Direction	<i>R</i> ² value	<i>P</i> value	Direction
Organic material (%)	0.247	0.006	Negative	0.024	ns	-
Silt (%)	0.387	0.013	Negative	0.042	ns	-
Sand (%)	0.193	ns	-	0.090	ns	-
Fine gravel (%)	0.263	0.050	Positive	0.007	ns	-

Mature seeds of *Ruppia megacarpa* were extracted from Core III from the Eastern arm of Waituna Lagoon. Five seeds were found from 35 – 33 cm depth, corresponding with a relatively low percentage of organic material.

A Principal Components Analysis (PCA) was conducted to determine the environmental correlates of *Ruppia* and *M. triphyllum* pollen abundance (Core I; Fig. 25). A PCA was constructed using data on sediment grain size, water content and organic content, with the pollen data plotted as supplementary variables (section 4.11). The primary axis (x-axis) represents the gradient of marine and freshwater influence, as indicated by the strong loadings of sand content and organic matter content. This axis explains 44% of the variance in the physical sediment data. The second axis primarily reflects the clay content of the sediment and explained 24% of the variance in sediment variables. The abundance of *Ruppia* pollen was strongly correlated to the primary axis, which explained 69% of the

pollen-sediment relationship. *Ruppia* loaded positively with sand content (marine influence) and negatively with organic material content (freshwater influence). In contrast, *M. triphyllum* correlated positively but weakly with organic material content (freshwater influence).

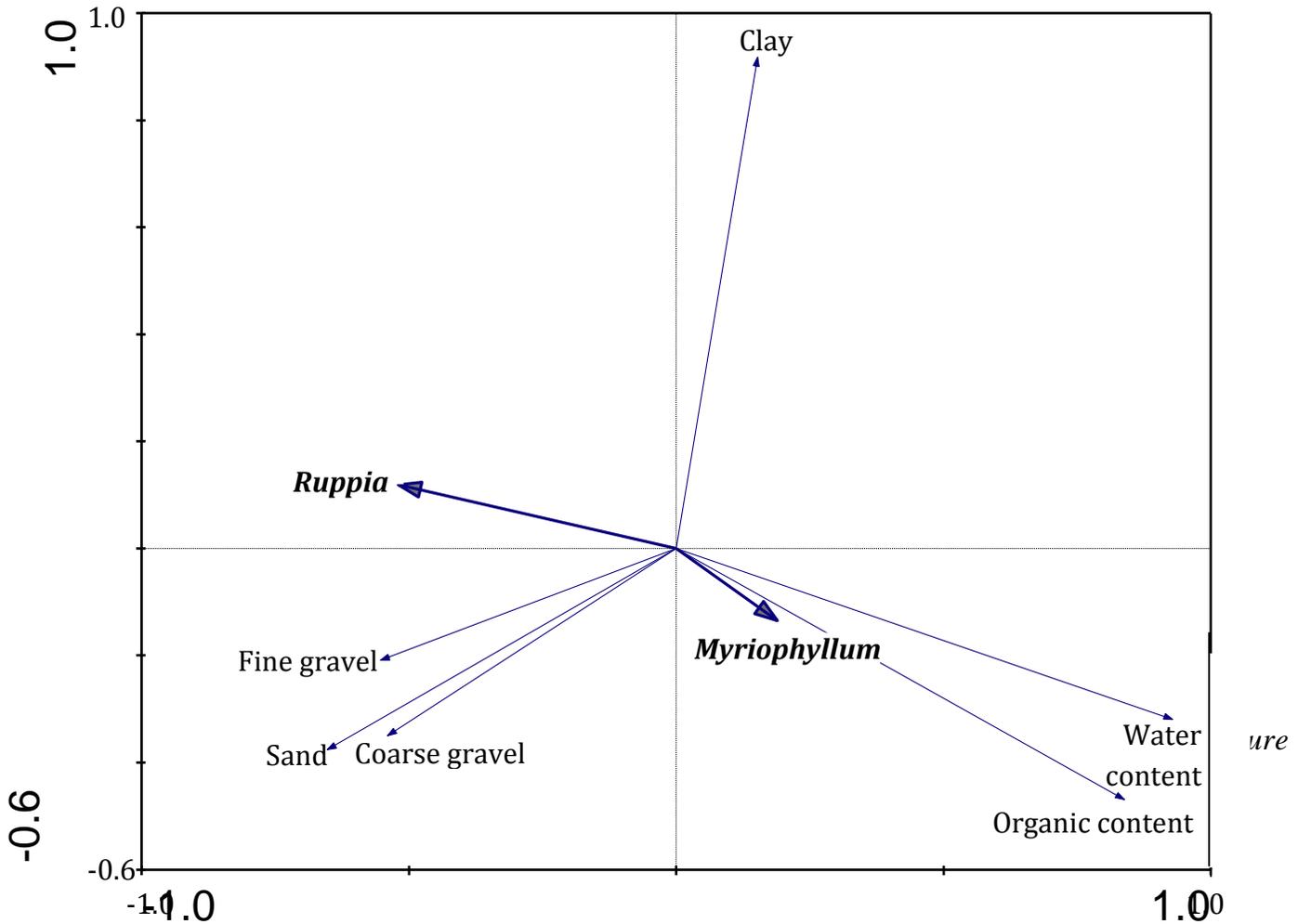


Fig. 25: Biplot of Principal Components Analysis (PCA) of physical sediment variables and the relative abundance of macrophyte pollen at Shand Bay (Core I), Waituna Lagoon. A PCA was conducted on the physical sediment variables. The pollen from the macrophytes *Ruppia* and *Myriophyllum triphyllum* were coded as supplementary variables and were plotted over the PCA of the sediment variables. Axis 1 explained 44% of the sediment characteristics and 69% of the pollen-sediment relationship. Axis 2 explained 24% of the sediment characteristics but only 4% of the pollen-sediment relationship

5.4 Intra-lagoon variation

This section focuses on comparing the replicate cores from Shand Bay (Cores I and II) with the core from the Eastern arm of Waituna Lagoon (Core III). Sediment shortening was evident in all cores and greatest in the Eastern arm (Core III; Table 7). The different depositional environments and different levels of sediment shortening between sites offset trends in the cores. As a result few sediment variables between the sites were significantly correlated (Table 8). The sand content was significantly negatively correlated between sites, highlighting the different deposition environments. The sediment density and percentages of water and organic material were significantly positively correlated between sites.

Table 7: Sampling location, sediment shortening and length for each core used in this study

Core number	Sampling location		Core length (cm)	Sediment shortening	
	Description	GPS		(cm)	(%)
I	Shand Bay	N2169945 E5395140	130	9	6.5
II	Shand Bay	E2169844 N5395165	83	5	5.7
III	Eastern arm	E2174845 N5395175	64	6.5	9.2

The absolute values of different variables also differed between sample locations, although most variables were similar between sites (Table 9). The organic content was much higher in Shand Bay (Cores I and II) than in the Eastern arm of the lagoon (Core III). The sediment grain size was also slightly different between sites, particularly the coarse gravel which was much more common in Core III.

The average sediment grain size between sites was similar (Table 9), but the trends and values with depth were heterogenous (Fig. 26). Sediment grain size in Shand Bay could not be used to predict the grain size in the Eastern arm of the lagoon (Fig. 26).

Table 8: Correlation matrix comparing cores from Shand Bay (Cores I and II) and the Eastern arm (Core III) of Waituna Lagoon

Variable	Core I versus Core III			Core II versus Core III		
	R^2 value	P value	Direction	R^2 value	P value	Direction
Density (g/ml)	-	-	-	0.115	< 0.001	Positive
Organic material (%)	0.102	0.010	Positive	0.589	0.033	Positive
Sand (%)	0.106	0.009	Negative	-	-	-
Water content (%)	0.208	< 0.001	Positive	-	-	-

Table 9: The average values for different variables tested in all cores. As Core III is 64 cm long only the top 64 – 0 cm of each core was included, to facilitate a direct comparison. The abundance of coarse gravel was standardised and is presented as the number of particles per mg of dry sediment

Variable	Core I (Shand Bay)	Core II (Shand Bay)	Core III (Eastern arm)
Density (g/ml)	-	1.37	1.48
Water content (%)	37.03	-	33.28
Organic material (%)	8.83	9.18	3.81
Clay (%)	0.11	-	1.04
Silt (%)	43.71	-	53.06
Sand (%)	45.87	-	39.89
Fine gravel (%)	10.31	-	6.01
Coarse gravel (# / mg sediment)	< 0.001	-	8.78

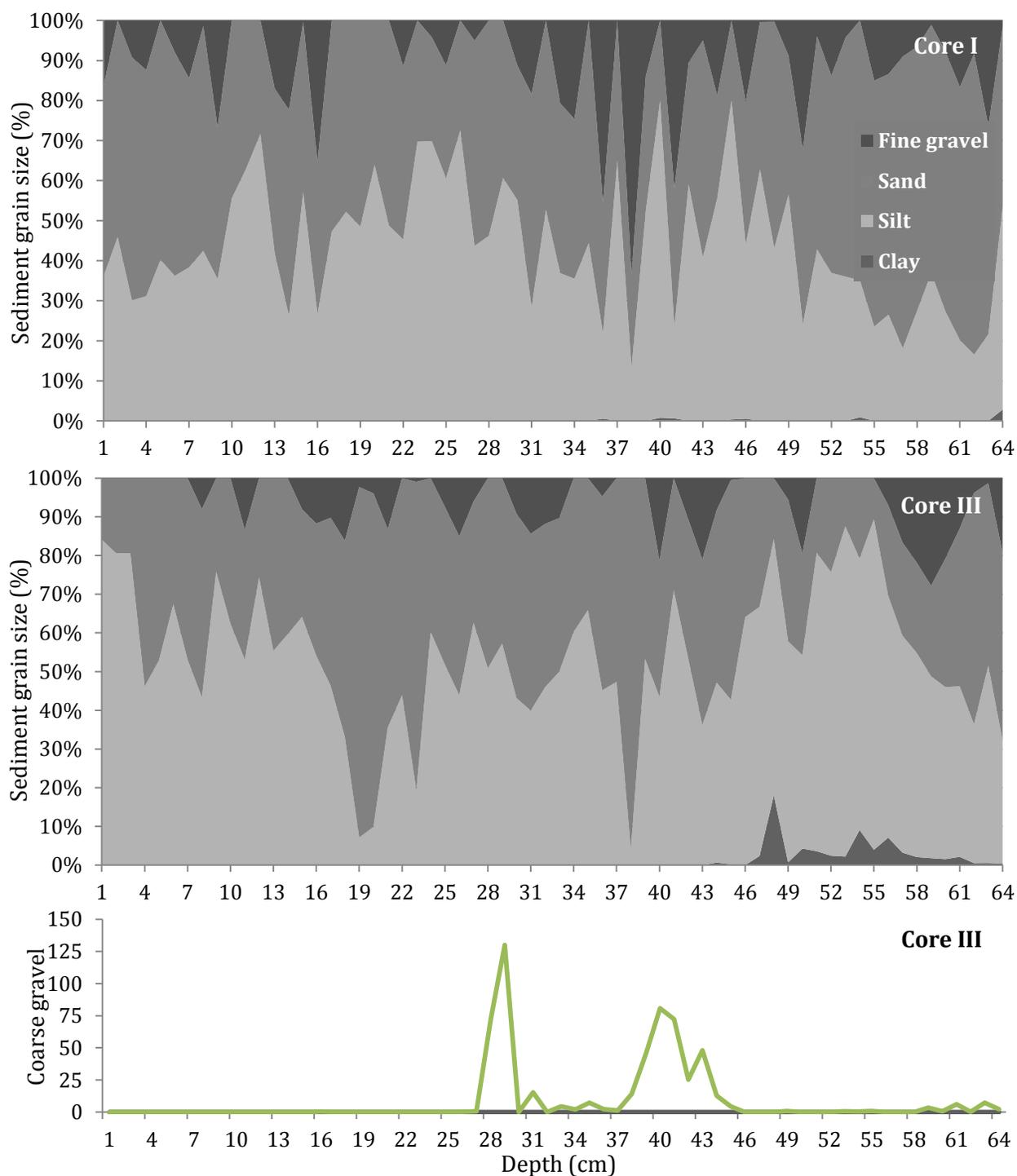


Figure 26: Sediment grain size in Cores I (Shand Bay) and III (Eastern Arm), Waituna Lagoon. The quantity of coarse gravel was standardised and is presented as the number of particles per mg of dry sediment, with data from Core I not displayed as the values were so low. $N = 64$

Trends in the sediment density, water and organic content also differed between sites (Fig. 27).

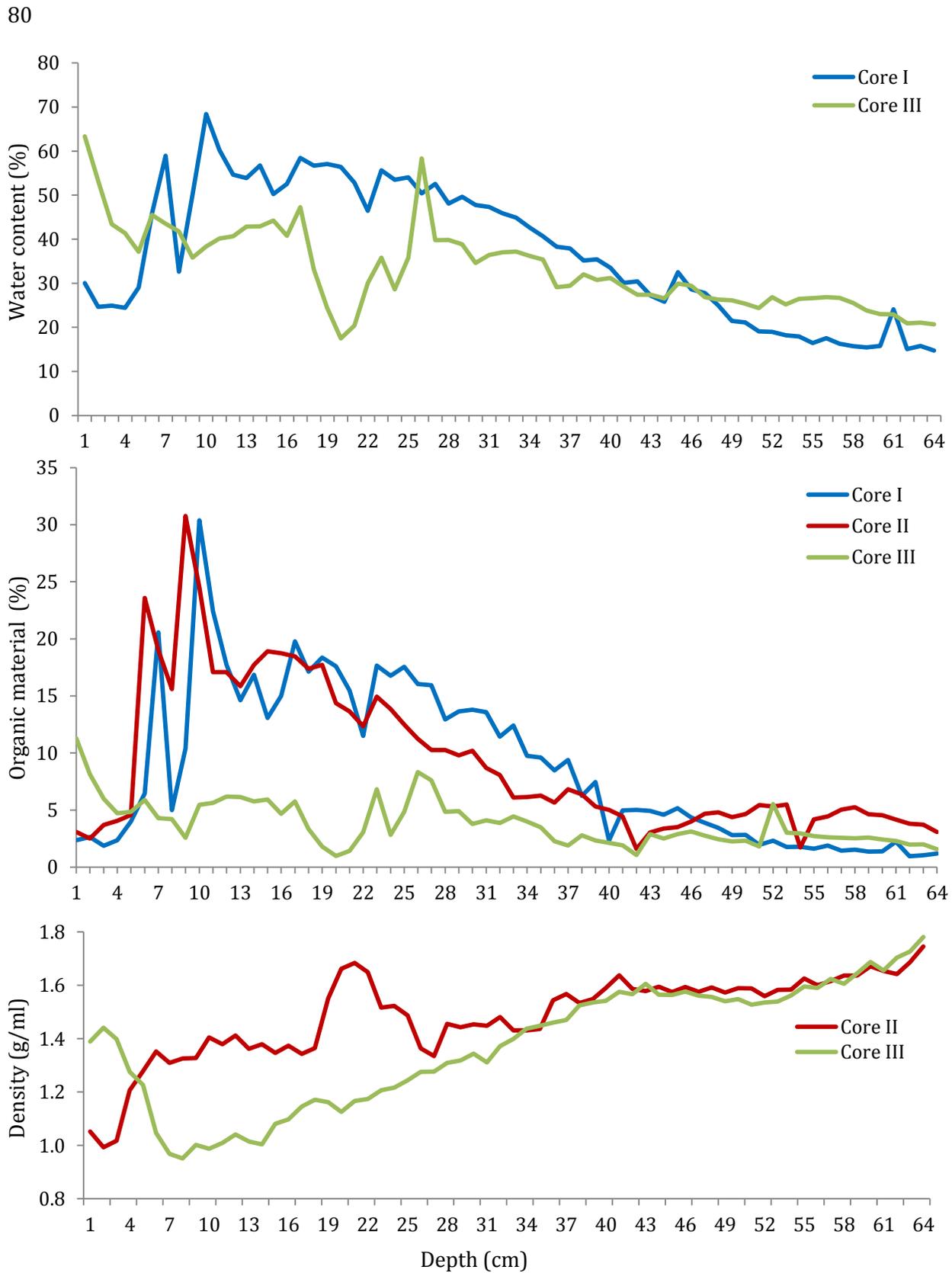


Figure 27: Trends in the sediment density and percentages of water and organic material in sediment cores from Shand Bay (Cores I and II) and the Eastern arm (Core III) of Waituna Lagoon. $N = 64$

6. Discussion

This chapter presents an analysis of selected results with a focus upon the three hypotheses. The environmental tolerances of most taxa identified at Waituna Lagoon during this study are outlined in Appendix C, and the utility of the methods in answering the hypotheses is presented in Appendix D.

The replicate cores from Shand Bay were highly similar (quantity of organic material significantly positively correlated - $R^2 = 0.648$, $P < 0.001$, *Ruppia* seeds absent in both cores), giving confidence in the validity of the results.

6.1 Inferred sediment chronology

Through linking the sediment depths with measurable time, sediment chronologies can enable researchers to distinguish between natural and anthropogenic variation. These chronologies are often constructed using ^{210}Pb , which is deposited in lake sediments from the catchment or atmosphere (Appleby and Piliposian, 2010). Unfortunately, ^{210}Pb dating of the sediments in Waituna Lagoon was unsuccessful (Appendix B.2). The lack of large shell or wood fragments, high error rates for bulk sediment dating and budgetary constraints prevented the analysis of ^{14}C and ^{137}Cs . Thus the sediment chronology was inferred from pollen and charcoal profiles.

Based upon these profiles it was inferred that the sediment at 50 cm depth in Core I (Shand Bay) was deposited in 1900 AD \pm 10 years. The deepest sample in which *Pinus radiata* (Monterey pine) pollen was identified was at 50 cm depth, and it was estimated that *P. radiata* first flowered in Southland in ca. 1900 AD (\pm 10 years; D. Lee and M. Schallenberg, pers. comm., 2010).

The percentages of sand and organic material, the charcoal density and the abundance of most indicator pollen species showed marked changes in the sediment at or around 50 cm depth. This lends confidence to the inference that this depth correlates with a period of increasing anthropogenic disturbance at Waituna Lagoon. The charcoal and pollen data had a zone from 60 – 30 cm where most changes occurred (Figs. 14, 15). Thus, this chronology implies that there was increasing anthropogenic activity in the Waituna Lagoon catchment

during the time corresponding with 60 – 30 cm depth, and that by 30 cm depth the lagoon and catchment had been heavily modified by European settlement.

Pteridium esculentum (bracken fern, formerly known as *Pteridium aquilinum* var. *esculentum*) is an indicator of fire disturbance which increased its range and abundance after human settlement in New Zealand (McGlone *et al.*, 2005). Often considered a weed, *P. esculentum* rapidly proliferates in farmland and after fires (McGlone *et al.*, 2005). In Waituna Lagoon *P. esculentum* had the highest relative abundance from 20 – 5 cm depth, and charcoal density was highest from 30 – 10 cm (Fig. 15). Thus the relative abundance of *P. esculentum* at Waituna Lagoon increased after fire. These fires appear to have become more frequent after the Waituna Lagoon catchment had been heavily modified by European settlement.

This is correlated with anthropogenic records from this time, which include frequent reports of large fires. For example, in 1953 a fire in the Seaward Bush Reserve (ca. 15 km northeast of Waituna Lagoon) destroyed 10,000 *P. radiata* trees; and a much larger portion of the same plantation was burnt in 1961 (Watt, 1971). Unfortunately the influx of charcoal cannot be conclusively correlated with any specific fires, but the regional fire history reinforces the inferred sediment chronology.

Fire was also used to transform large areas of the Waituna catchment into pasture, although there was a relatively low charcoal density during this time period. The first phase of pasture development around Waituna Lagoon was deforestation through logging, to support the forestry industry and generate income (Floyd, 1980). This is seen in the construction of the Siberia Timber Mill on the banks of the lagoon in 1904 (Waghorn and Thompson, 1989). Following logging, pasture was often developed and maintained through the use of fire, particularly to eliminate or reduce *P. esculentum*, which rapidly colonised pastoral land. Beattie (1979) recorded a fire in Southland which was used to assist travel between settlements:

The vegetation was an amazing accumulation of flax, fern and debris that had been collecting for centuries, grown up and decayed again and again, while what was living was rank and high. The growth was as high as their heads and impeded progress so much that the white man put a match to it and as there was a stiff breeze a tremendous “burn” was the result, the smoke being seen from Inchclutha.

Another account in the same book reads:

... the air was sometimes filled with smoke from the fires that were burning off the rank vegetation from this portion of Southland's surface. ... One would frequently see a line of flames, many miles in length, rolling up and down hills, and along flats before the wind ...

A smaller increase in charcoal density from 110 – 90 cm depth may be due to Māori deforestation or lightning fires, though the latter was rare in the South Island (McWethy, 2010).

Artificial management at Waituna Lagoon began in 1908 (Thompson and Ryder, 2003). The inferred sediment chronology of Core I (Shand Bay) dated 50 cm depth as 1900 AD \pm 10 years. Therefore, sediment from Shand Bay deeper than 50 cm is attributed to a natural environment.

6.2 Hypothesis one: Opening regime

This study aimed to reconstruct Waituna Lagoon's natural opening regime and *Ruppia* abundance. The hypothesis that under a natural opening regime environmental variations within Waituna Lagoon were less frequent but more extreme was tested. This hypothesis was based upon the frequent artificial openings of Waituna Lagoon, which maintain the water level well below the natural maximum level (Johnson and Partridge, 1998). Opening the lagoon at a relatively low water level should result in a smaller cut in the barrier bar, as the hydraulic head is smaller (Haines, 2006). This potentially results in shorter openings (i.e. shorter periods of marine influence). The barrier bar leaks at high water levels. Therefore the water levels should be stabilised when the lagoon is full, until an excess of water naturally overtops the barrier bar. This stabilisation may result in longer periods in a freshwater state. A conceptual model for the open, closed and transitional states of Waituna Lagoon's opening regime is presented below (Fig. 28).

The historic opening regime of Waituna Lagoon was reconstructed using the changes between the percentages of organic material and sand in the sediment. A sediment content of >3% organic matter was inferred to be an indicator of periods when the lagoon was closed (based upon the pattern of distribution in Fig. 19). During closed periods the lagoon was filling with freshwater and accumulating organic material (Fig. 28). This enrichment of organic material is common in ICOLLS (intermittently closed and open lakes and lagoons;

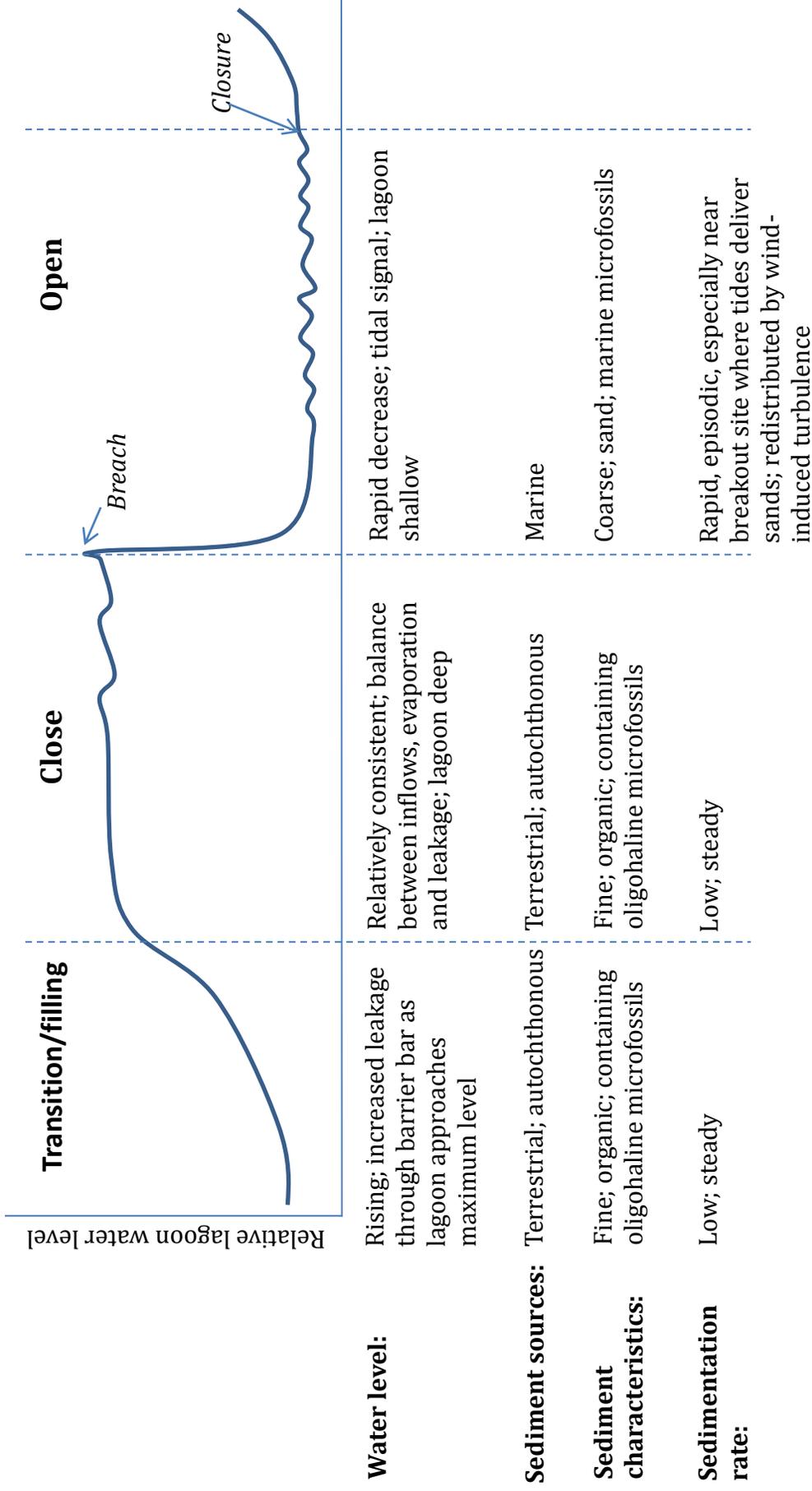


Figure 28: A conceptual model of the water level and sediment sources / characteristics / deposition during the three phases of the Waituna Lagoon opening regime (source: M. Schallenberg, unpubl.)

organic material is common in ICOLLs (intermittently closed and open lakes and lagoons; Spooner and Maher, 2005), and without an outlet to remove this material it accumulated in the lakebed. The organic matter was probably primarily terrestrial in origin, entering Waituna Lagoon from its tributaries and dense surrounding vegetation. Organic material was significantly positively correlated with silt and negatively correlated with sand ($P < 0.001$; Table 4), suggesting that during closed phases the sediment was more fine-grained and humic.

Sediment with $> 58\%$ sand content indicates periods when Waituna Lagoon was open and had a stronger marine influence. When open, sand would have been pushed into the lagoon by tides via longshore drift (McLean *et al.*, 2003); and the increased currents and wave action (due to lowered water level) would have washed fine and low density organic material and silt out of the lagoon. When the lagoon was closed, little sand would have been available for deposition within the lagoon as the small catchment is dominated by peat soils (Johnson, 2001) and is drained by small, low gradient streams (Thompson and Ryder, 2003).

Organic material and silt were significantly negatively correlated with sand ($P < 0.001$; Table 4). As a result these proxies appeared to be useful indicators for reconstructing the opening regime, while also indicating the potential for quartz dilution. However, quartz dilution does not invalidate the use of sand/organic material layers as indicators of the closed/open state of the lagoon. This inference was strengthened by previous studies on ICOLLs. For example, high levels of organic material can be a stressor in ICOLLs due to their periodically restricted outflows (Spooner and Maher, 2005); and as a result of urbanisation some coastal lakes are artificially opened to reduce siltation and nutrient enrichment (Dye and Barros, 2005). These studies both demonstrate that organic material builds in coastal lakes when they are closed. Further, it was reported that sand entered the Australian ICOLLs Lake Conjola and Narrabeen Lagoon from the ocean when they were open (McLean *et al.*, 2003; Morris and Turner, 2010).

Similar trends between sand, silt and organic content were seen in Shand Bay and in the Eastern arm of Waituna Lagoon, though they were less significant in the shorter core from the Eastern arm (Table 4). In Shand Bay it was inferred that the sediment at 50 cm depth was deposited in 1900 ± 10 years. Waituna Lagoon was first artificially opened in 1908, and has been opened frequently ever since. This may explain why there was not a strong signal

of openings and closures in the Eastern arm (Core III), and why an opening regime could not be reconstructed using this core.

The opening regime was reconstructed in Core I (Shand Bay) using two independent methods, one statistical and the other inferential. Both methods employed the same data. The first method was a single-blind study wherein the sample identity (depth) was withheld. The participant determined which samples belonged to open, closed or transitional phases based upon a scatterplot and thresholds of the percentages of organic material versus sand (Fig. 19). Transitional phases referred to the lagoon filling phase, with the exception of a single sample during a disturbance event. Thresholds were determined by clusters on the scatterplot. The second method involved the reconstruction of the opening regime in a temporal context, based upon interpretation of the line graph of organic material and sand versus depth (Fig. 20).

The results of the two methods were significantly similar ($X^2 = 29.28$, $DF = 1$, $P < 0.01$), with 90.1% of samples below 39 cm attributed to the same state (Table 5). The methods only differed with respect to which samples were identified as transitional, and one method could not categorise sediment from 39 – 6 cm. These differences were primarily caused by the percentage of organic material, which was much higher from 39 – 6 cm (Fig. 20).

The percentage of organic material increased after 1900, probably reflecting increased productivity due to increased nutrient enrichment (which is known to have occurred; Thompson and Ryder, 2003). It was also very low in the bottom of the core (130 – 115 cm; Fig. 20). As the percentage of organic material is non-linear with depth and patterns were clearly evident in the deeper sediments (Fig. 20) this trend probably does not reflect decomposition of organic material in the deeper, older sediments. Without a detailed sediment chronology it was not possible to correct for any decomposition (Ruiz-Fernández *et al.*, 2002).

There was much more sediment in each phase under a natural opening regime (Fig. 20). This could be caused by the lagoon remaining open and closed for longer periods of time or by large depositional events. The catchment of Waituna Lagoon is small (210 km² - Schallenberg *et al.*, 2010), so large depositional events during closed phases are highly unlikely. Therefore the lagoon was probably closed for longer periods of time in the past. The length of these phases cannot be inferred without a detailed sediment chronology.

The current sea level is ca. 17 cm higher than when artificial management in the lagoon began (Hannah, 2004), creating the potential for more seaward sediment exchange during openings. No large depositional events were seen during artificial management (Fig. 20). Although sea levels were lower under a natural regime the barrier bar cuts would have been larger due to the larger hydraulic head (Haines, 2006). However, it is not likely that there was a large depositional event each time the lagoon was open. Therefore it appears that under a natural opening regime, Waituna Lagoon remained in open and closed states for much longer periods than at present. The large difference in the sediment record between open and closed states suggests that the ecosystem had time to equilibrate to freshwater and estuarine states.

Under a natural regime lagoon closure took much longer than openings (transitions of 10 – 15 cm versus 1 – 2 cm, respectively; see the “transitional” phases in Fig. 20). Under a natural regime, rapid openings would be expected due to the large hydraulic head. Fast closings are consistent with small breaches of the barrier bar (Baldock *et al.*, 2008), therefore the slow closures observed under a natural opening regime are an expected result of large breaches. The observed difference in the transition dynamics between natural openings and closings may be affected by bioturbation.

Bioturbation by tidal resuspension, molluscs (especially snails and bivalves), polychaetes and other fauna would be expected to mix sediment vertically at the surface of the lakebed (White and Miller, 2008), smoothing potential indicators of abrupt environmental change (Dearing and Zolitschka, 1999). In some sediments trace fossils enable quantification of bioturbation (Marenco and Bottjer, 2011), but indicators are often poorly preserved (White and Miller, 2008). Bioturbation does not seem to be a large issue at Waituna Lagoon as there was no evidence of it during physical examination of the sediment cores. Specifically there were no polychaetes holes, and no large shells indicating bioturbation by bivalves; and there were very sharp, undisturbed layers between sediment types. Snails were found in the cores, but bioturbation could not be quantified due to the lack of physical traces. Relatively large influxes of sand when the lagoon opened may prevent bioturbation by smothering infaunal communities (Lundquist *et al.*, 2006; Cook, 2008).

The sole exception to the observed natural trend of fast openings and slow closures was observed at 66 – 63 cm (Fig. 20). As the changes were so dramatic and quickly reversed it is interpreted as a disturbance event. It does not correlate with any known storm or flood

event; however, based on the inferred chronology it could indicate early anthropogenic disturbance following permanent settlement around Waituna Lagoon.

The frequency of change between open and closed states became much more rapid after 1908 (Fig. 20), when artificial openings began (Thompson and Ryder, 2003). Before that time the lagoon appeared to reach long-term freshwater equilibria. From 39 – 6 cm depth the opening regime was classified as “frequent openings” as the average percentage of sand content remained relatively stable (Fig. 20), although the variation and percentage of organic material in the sediment increased markedly (Fig. 23). Within this phase there were clear short-term variations. In the upper core (6 – 0 cm), sediment characteristics again suggested an intrusion of sand, possibly reflecting the phase of longer openings from 2003 – 2006 (C. Jenkins, pers. comm., 2011).

The above data and inferences support the hypothesis that under a natural opening regime environmental variations within Waituna Lagoon were less frequent but more extreme than under the current, managed regime. Thus, it appears that management has altered the dynamics of this ecosystem in ways that are interpretable from the sediment record.

Key findings: Evidence from sediment cores supported the hypothesis that under the natural opening regime environmental fluctuations within Waituna Lagoon were less frequent but more extreme. The alternate marine and freshwater phases appeared to last longer and equilibrate to a greater extent than under the managed opening regime.

6.3 Hypotheses two and three: *Ruppia*

Ruppia is a native aquatic macrophyte which currently dominates the macrophyte community of Waituna Lagoon (Robertson and Stevens, 2009). This study aimed to discover whether *Ruppia* was present and dominant in Waituna Lagoon when subjected to a natural opening regime. Two hypotheses were tested: that *Ruppia* was not present under the natural opening regime; and that it was present but not dominant.

Ruppia is a key component of Waituna Lagoon (Stevens and Robertson, 2007), and its abundance is being regularly monitored by Environment Southland. If *Ruppia* had colonised and become dominant in Waituna Lagoon as a result of the altered opening regime or

increased nutrient concentrations, then future restoration goals should take that into account.

These hypotheses were addressed using pollen analyses in Core I (Shand Bay) and macrofossil analyses in all cores (Shand Bay and the Eastern arm of the lagoon). *Ruppia* pollen was found to 100 cm depth, 50 cm deeper than the onset of *Pinus radiata* pollen (Figs. 14 and 24). Thus, *Ruppia* was present in Waituna Lagoon prior to European arrival. It is, therefore, a natural and intrinsic component of the Waituna Lagoon ecosystem. Hypothesis two (“that *Ruppia* was not present in Waituna Lagoon under a natural opening regime”) was rejected.

It is not known when *Ruppia* colonised Waituna Lagoon. Given the inferred chronology, it is clear that it was introduced before European settlement occurred in the area, but as a detailed robust chronology could not be determined for the core, it was not possible to determine the oldest date for *Ruppia* pollen in the core. Only the upper 110 cm of Core I retained enough pollen for reliable analysis, and *Ruppia* was found to 100 cm depth. It is interesting that no *Ruppia* pollen was found at 110 cm depth, as this correlated with a period when the lagoon is inferred to have been open, and *Ruppia* pollen was more abundant when the lagoon was open (Table 6; Fig. 25).

In total 55 *Ruppia* pollen grains were found in Core I, with an average of only 3.67 grains per sample (Appendix B.4). Given the low density of *Ruppia* pollen in the sediment it is possible that its absence at 110 cm depth is due to the limitation of small sample sizes rather than its absence within the Lagoon. This is supported by the absence of *Ruppia* pollen at 10, 15, 20 and 30 cm depth despite its subsequent reappearance in the pollen counts at 5 and 25 cm depth.

Ruppia pollen is generally inversely correlated with the pollen of the oligo-meso-haline macrophyte *Myriophyllum triphyllum* (Fig. 24). *Ruppia* was periodically dominant under a natural opening regime (Fig. 24); therefore hypothesis three (“that *Ruppia* was not dominant in Waituna Lagoon under a natural opening regime”) was also rejected.

As the pollen of both taxa were present in almost every sample examined, it appears that Waituna Lagoon may not have undergone regime shifts between macrophyte- and phytoplankton-dominated states (Schallenberg and Sorrell, 2009) in the past. Rather, the macrophyte taxa may exhibit alternating dominance in the lagoon because *Ruppia* pollen counts were strongly correlated with the lagoon being open, and *M. triphyllum* pollen

counts were weakly correlated with the lagoon being closed (Table 6; Fig. 25). This is important, as there is increasing concern that Waituna Lagoon will soon “flip” into a phytoplankton-dominated state (Environment Southland, 2011; Hamill and MacGibbon, 2011).

Despite tolerating both fresh and brackish waters (Brock, 1982, 1983; Short and Neckles, 1999) *Ruppia megacarpa* and *polycarpa* germinate most successfully in freshwater (Brock, 1982; Vollebergh and Congdon, 1986), suggesting that recruitment should depend on the lagoon being closed. However, *Ruppia megacarpa* is a perennial, growing vegetatively for a number of years (Brock, 1982, 1983). The association with open phases may be due to depth requirements.

In Waituna Lagoon *Ruppia polycarpa* inhabits areas from 0 – 0.5 m depth, and *R. megacarpa* from 0.5 – 3 m depth (Stevens and Robertson, 2007). Under a natural regime, water levels may have reached ca. 4 m when closed before the barrier bar was breached (Johnson and Partridge, 1998). The higher water levels may have restricted the distribution of *Ruppia* to the shallower margins of the lagoon. This is probably correlated with light availability and reproduction. Some studies suggest that *R. megacarpa* has a low light requirement (West, 2004) but the waters of Waituna Lagoon have very low clarity so it is probably light limited in this system (Schallenberg and Tyrrell, 2006). Further, inflorescences must be lifted to the water surface for fertilisation (West, 2004), so it is probably depth limited as well. Riddin and Adams (2008) found a strong correlation between water depth and the abundance of *R. megacarpa*, with a two month lag between changes in depth and abundance.

Ruppia pollen may be more abundant during recent open phases because of the associated reduction in the nutrient load, as high nutrient availability is a stressor for macrophytes (Ralph *et al.*, 2006). However, *Ruppia* today cannot tolerate long periods of high salinity; therefore it is likely that it was not abundant for the entirety of the open phases, investing its energy in reproduction for re-establishment after the lagoon closed.

M. triphyllum was weakly correlated with closed periods in Waituna Lagoon, which is consistent with its environmental tolerances. A relatively tall native New Zealand macrophyte, *M. triphyllum* commonly attains heights of 1 – 2 m (Rattray *et al.*, 1991; Kelly and Hawes, 2005). It is a primarily freshwater species, though it also tolerates brackish conditions (Orchard, 1979) and prefers relatively slow water velocities (Lacoul and

Freedman, 2006), indicating that it may be stressed by wave action. A strongly competitive ruderal (Riis and Biggs, 2001), *M. triphyllum* probably competed favourably with *Ruppia* when the lagoon was closed, but may have been restricted to more sheltered areas of the lagoon and areas near freshwater inflows when the lagoon was open.

Despite the near-continuous presence of *Ruppia* pollen in Core I (Shand Bay), seeds of *R. megacarpa* were only found at 35 - 33 cm depth and only in Core III (Eastern arm). A total of 5 seeds were found, although 78.35 cm³ of sediment was analysed. Brock (1983) stated that *R. megacarpa* establishes a “permanent seedbank” within the sediment. The spiked *Ruppia* seeds are probably not distributed evenly through the sediment. In Lake Ellesmere where *Ruppia* was once common (Gerbeaux 1989) they often form balls of seeds which roll on the lake surface and are occasionally dragged up by fishers (M. Schallenberg, pers. comm., 2011). *Ruppia* seeds were also absent from sediment core samples collected from three sites in Lake Ellesmere (M. Schallenberg, pers. comm., 2011). This phenomenon has received little attention, and is almost absent in existing literature. However, balls of *Ruppia maritima* were recorded in two Canadian lakes by Olson *et al.* (2005). These balls may be formed by wave action (Olson *et al.*, 2005) and can be as large as “small watermelons” (Kantrud, 1991).

Ruppia species and *M. triphyllum* are still present at Waituna Lagoon, and the surficial sample showed a relatively high pollen abundance of both species (Fig. 24). This is the first time in the sediment record that both *Ruppia* and *M. triphyllum* pollen have peaked in abundance at the same time. However, there was a recent period (20 – 10 cm depth) when neither taxon was found. These results indicate that present management may favour both species, but macrophytes may be more vulnerable under certain conditions brought about by water level management.

Although macrophytes are persisting under the present opening regime, indications of their vulnerability in this study and others (Robertson and Stevens, 2009; Hamill and MacGibbon, 2011; Environment Southland, 2011) indicates that Waituna Lagoon may be approaching a tipping point, resulting in a change to a turbid phytoplankton dominated system. This is a common result of high levels of eutrophication and results in poor water quality, which often does not improve (e.g. Lake Ellesmere/Te Waihora, Schallenberg *et al.*, 2010). Should Waituna Lagoon change to a phytoplankton-dominated ecosystem, the

current light levels and opening regime would prevent the re-establishment of *Ruppia* in Waituna Lagoon (Schallenberg and Tyrrell, 2006).

Key findings: *The hypotheses that Ruppia was not present or dominant in Waituna Lagoon under a natural opening regime were not supported. The analysis of pollen grains from the sediment cores indicates that Ruppia was established in Waituna Lagoon before both the advent of permanent European settlement in the catchment and artificial management of the opening regime. As such, it is a natural and intrinsic component of the Waituna Lagoon ecosystem.*

Historically Ruppia pollen was more abundant when the lagoon was open, possibly due to light and reproductive limitations in the bottom waters when the lagoon was closed. Under the artificial opening regime the abundance of Ruppia and Myriophyllum triphyllum pollen has been extremely variable. The present management may favour both species, but there are indications that they may be more vulnerable than under a natural opening regime. The abundance of Ruppia pollen is still relatively high, but certain conditions may cause both macrophytes to be vulnerable to collapse.

6.4 Intra-lagoon variation

In addition to answering the main objectives and hypotheses of this study a limited assessment of intra-lagoon variation was conducted. Shand Bay was selected as the primary site for analysis as it was more sheltered and therefore likely to have a more continuous sedimentary record. A site in the Eastern arm was also sampled to assess whether results from Shand Bay could be extended across the entire lagoon. This was also intended to inform future research, by establishing whether different environmental trends were evidenced in different areas of the lagoon.

Comparing the sites is complicated by the lack of a sediment chronology. The transition to a modified system was inferred in Core I from Shand Bay, but no dates are available for Core III from the Eastern arm. This complicates comparisons as the rate of sedimentation at each site is unknown. The sites were in different deposition environments, so intra-lagoon variation was expected, including differences in the sedimentation rates. Further, the site in the Eastern arm is unsheltered from a nearby section of the barrier which periodically

breaches to the sea (sites shown in Fig. 12; the weak barrier is shown in Fig. 5). During such times it may experience rapid erosion and/or deposition. This is likely to produce a different sedimentary record to the sheltered Shand Bay.

Without an available chronology an equal sedimentation rate was assumed to enable intra-site comparisons. Variables at each site showed similar relationships (e.g. Table 4) but different patterns of variation (e.g. Fig. 27). This is seen in reconstructions of the opening regime. Both sites evidenced negative relationships between sand and organic material, and sand and silt; and positive relationships between organic material and silt (Table 4). However, patterns in this variation were markedly different (Core I - Fig. 20; Core 3 - Fig. 22). The surficial samples in each core indicated a marine phase, with broadly similar levels of organic material and sand in each core. However, deeper in the core the data did not appear to covary. Other than the modern samples which were correlated with Shand Bay, open, closed and transitional phases could not be clearly distinguished in the Eastern arm using these sediment characteristics. Sediment from ca. 22 - 18 cm depth appear to indicate an open state, but no other clear signals could be seen (Fig. 22) as understood in Core I from Shand Bay.

The percentage of organic material was much lower in the Eastern arm (Core III) than Shand Bay (Core I; Table 9). This may have complicated interpretation of the opening regime, and may be correlated with the sampling locations. Core I in Shand Bay was much closer to the lagoon margin than Core III from the Eastern arm (Fig. 12). The lagoon margins are covered with abundant vegetation, often overhanging the lagoon waters or growing to the shore. This provides abundant terrestrial organic material for deposition. A number of seeds were found in Core III, most from the native sedge *Baumea tenax* (Fig. 34) which grows around Waituna Lagoon (Thompson and Ryder, 2003). The quantity of seeds in the Shand Bay sites was not measured for comparison due to resource constraints.

The greater distance of Core III from the shore probably caused the lower percentage of organic material in the sediments. Therefore indicators of the opening regime may be most clearly read in cores collected near the lagoon margin. Alternately, the lack of clear signals of the opening regime in Core III may be due to its short length, particularly if the sediment was all deposited after European settlement, as the lagoon did not appear to equilibrate for long periods of time under artificial management (Fig. 20; Table 5). It may also be caused by waves of rapid erosion and/or deposition when the Hansens Bay barrier breached.

Some variables were significantly positively correlated between sites (Table 8). Interestingly, sand was significantly negatively correlated between sites. This further emphasises the different deposition environments, and different patterns of variation at both sites. The sediment grain size was heterogenous between sites (Fig. 26), and sediment grain size in Shand Bay could not be used to predict the grain size in the Eastern arm of the lagoon. Notably, the core from the Eastern arm has much more coarse gravel (Fig. 26; Table 9), probably because of its closer proximity to the sand/gravel barrier bar. Sediment grain size is highly interrelated with sediment density and water content (Scalbeck *et al.*, 2010), which also had different patterns of variation between sites (Figs. 26 and 27).

Key findings: *Sedimentation patterns were different at two sites in Waituna Lagoon – a deep, wind-exposed site was different to a shallow, sheltered area. Downcore variation in sediments and sediment constituents at Shand Bay suggested variation in the opening regime, which could not be constructed in the core from the Eastern arm. Unfortunately, without sediment chronologies a detailed, robust comparison of sedimentation patterns at the two sites was not possible.*

6.5 Potential limitations

6.5.1 Representativeness of sampling sites

Sampling sites were selected to cover two potentially different sedimentary environments – the sheltered Shand Bay, and a wind- and tide-exposed section of the Eastern arm.

Interestingly, the signals of lagoon opening and closure were much stronger in Shand Bay. The sheltered nature of Shand Bay potentially dampened the signals of lagoon opening and closure. However, the cores at this site should have had a less episodic sediment record and would be less disturbed by wind events operating over a large fetch, potentially resuspending and redistributing sediment.

The poor correlations between many sediment core variables at the two sites (Tables 8 - 9, Figs. 26 - 27) indicates that conditions related to sedimentation in Waituna Lagoon are so dynamic that clearly interpretable signals of the lagoon's long term conditions are more

clearly seen in cores from the sheltered Shand Bay. The study was limited in its ability to draw strong conclusions about intra-lagoon variability as only two sites were sampled; however this was not a major focus of the study and does not affect the interpretation of key results.

It is assumed that the results from the Shand Bay core better reflect conditions and dynamics of the entire lagoon because extreme episodic events would not dominate the sediment record.

6.5.2 *Sediment chronology*

Through linking the sediment depths with measurable time, sediment chronologies can enable researchers to distinguish between natural and anthropogenic variation. These chronologies are often constructed using ^{210}Pb , which is deposited in lake sediments from the catchment or atmosphere (Appleby and Piliposian, 2010). Unfortunately, ^{210}Pb dating of the sediments in Waituna Lagoon was unsuccessful. Indeed, a previous attempt to use ^{210}Pb dating in lakeshore and wetland sediments in this system also did not find sufficient ^{210}Pb to generate a robust timeline (Cadmus, 2004), and an attempt to date sediment from Lake Waipori (Otago) had similar problems, whereas the method was successful in Lake Waihola (Otago; M. Schallenberg, unpubl. data). Thus, in some coastal lakes and lagoons in the South Island amounts of lead sedimentation are insufficient for ^{210}Pb dating. This may be caused by too little atmospheric deposition, or the lagoons may resuspend and wash out fine organic sediments, to which the lead is bound.

The ^{210}Pb data is presented in Appendix B.2 (Table 10). A tentative ^{210}Pb chronology was modelled by J. Cornett from MyCore Ltd, but this did not work as ^{210}Pb levels were so low that it was difficult to distinguish the signal from background activity. Following discussion with J. Cornett (MyCore Ltd), M. Schallenberg (University of Otago) and D. Lee (University of Otago) it was decided that, due to the very low quantities of ^{210}Pb in sediments of Waituna Lagoon, it was not possible to use this method to accurately date the sediments.

The lack of a robust timeline for the cores was a limitation as it prevented correcting for the potential decomposition of organic material with depth and corrections for sediment compaction between sites. These analyses would have aided the interpretations. It also prevented linking many changes in the sediment with documented historical events in the

catchment, such as the advent of farming. Without a ^{210}Pb sediment chronology, Waituna Lagoon's transition from a natural state to an ecosystem under strong anthropogenic influence had to be inferred from other sediment variables measured (section 6.1).

6.5.3 Core shortening

Core shortening was a methodological problem which was quantified in this study. It is a common phenomenon wherein the length of the recovered core is shorter than the depth the core penetrated the sediment (Morton and White, 1997). In this study core shortening was attributed to sediment bypassing and thinning, whereby softer sediments were forced aside during coring due to frictional resistance (Morton and White, 1997; Oliver *et al.*, 2009). Termed "lateral displacement", this occurs as softer sediments lack the strength to force denser sediment layers further into the core tube (Morton and White, 1997). It may have happened in all cores as sand and gravel layers were interspersed with layers of silt and peat.

Core shortening was not corrected for as it was a small effect (always < 10% of the core length) and was likely to be variable for different strata in the cores. Thus, a linear correction wasn't applied. Core shortening is a limitation of this study and a common limitation of most sedimentological studies (Morton and White, 1997).

6.6 Recommendations for future paleolimnological studies

Further paleolimnological studies are recommended, to strengthen the understanding of the dynamics of Waituna Lagoon. Limitations of the present study and knowledge gaps identified are listed below, along with recommendations for future research.

This study was limited by the inability to successfully establish a sediment chronology using ^{210}Pb . It is recommended that numerous cores be taken from throughout the lagoon to find suitable material (e.g. articulated shells or wood) for ^{14}C dating. If no suitable material can be found, it is recommended that bulk sediment organic C dating through ^{14}C be conducted using sediment from ca. 100 – 80 cm depth in Shand Bay. The sediment at this depth has a relatively high percentage of organic material, and was probably deposited under a natural opening regime before Waituna Lagoon became highly modified by

anthropogenic activity. As the sediment in Waituna Lagoon is largely peat, the organic material should be microscopically analysed, and fragments selected which reflect biomass produced within the lagoon such *Ruppia* seeds, pollen and roots. The reservoir effect should be corrected for. This analysis could not be completed as part of the present study due to time constraints.

It appears that the opening regime is best reconstructed using cores from relatively shallow, sheltered areas of Waituna Lagoon. Furthermore, under a natural opening regime *Ruppia* may have been restricted to shallow areas when the lagoon was closed. The opening regime and density of *Ruppia* are key elements of the ecology of Waituna Lagoon (Schallenberg and Tyrell, 2006). Therefore, it is recommended that future paleolimnological studies include cores from shallow, sheltered areas near the margins of the lagoon. Recommended coring sites should not be close to present or historical breaches of the barrier bar, so sites along the northern fringe of the lagoon and sheltered embayments such as Shand Bay are particularly recommended.

Core shortening should be measured for each core as it can vary between sites. A pilot study could conduct simple analyses such as loss on ignition (water and organic content) and measurements of sediment grain size on many cores throughout the lagoon. In this way, sedimentation patterns in different areas of the lagoon could be compared with the aim of selecting sites to optimise the potential for historical reconstructions. This study would be particularly informative if cores from a range of deposition environments could be reliably dated.

Little research has been conducted internationally about the formation or proliferation of *Ruppia* seed balls, with the only information available for *Ruppia megacarpa* and *polycarpa* being anecdotal. Further research into this area is recommended, as understanding this dynamic is critical for accurately interpreting microfossil records to reconstruct historic *Ruppia* abundance.

Other informative indicators include nitrogen, phosphorous and diatoms. Nitrogen and phosphorous could be used to reconstruct the nutrient profile and determine whether Waituna Lagoon has experienced eutrophication in the past; diatoms are useful proxies for water and salinity levels. These proxies could not be included in the present study due to time constraints. *Daphnia ephippia* and the foraminifer *Ammonia beccarii* were found in the sediment core from the Eastern arm. These taxa are ecologically informative, but had

limited use in this study as their distribution could not be correlated with the inferred sediment chronology. The macrofossil analysis in which they were found was not part of the original research plan, and when these taxa were discovered insufficient sample size was available in the Shand Bay cores for the analysis. Analyses of these macrofossils could be useful in future studies in Waituna Lagoon, as these taxa are valuable proxies of salinity (Appendix C.1, C.4).

6.7 Summary: A brief environmental history of Waituna Lagoon

The conceptual model of the natural state of Waituna Lagoon (Fig. 10) appears to be supported by the data gathered; with the exception that *Ruppia* was abundant under a natural opening regime. Based upon the above interpretation of the data, the following is a summary and explanation of the reference condition of Waituna Lagoon, and how it has changed as a result of anthropogenic activities.

Most ICOLLs are characterised as mostly open or mostly closed (Haines, 2006). Under the managed opening regime Waituna Lagoon fluctuates between being mostly open or closed (Fig. 7). It appears that Waituna Lagoon was naturally a lake which infrequently opened to the sea. These openings may have lasted for extended periods of time, and were caused by the lagoon water levels rising to a high level (Johnson and Partridge, 1998).

As the water levels rose the amount of leakage through the barrier increased, allowing the lagoon to stay closed for longer (Schallenberg *et al.*, 2010). The high water levels appear to have limited macrophyte distribution, restricting *Ruppia* to the shallower margins of the lagoon due to the high humic acid content and low water clarity of the freshwater in the system. When water levels were already very high and rose rapidly, the lagoon waters would breach the seaward barrier. The large hydraulic head caused scouring, creating a large and deep opening in the barrier. Because the water levels were naturally much higher than at present the hydraulic head would have been greater, potentially causing a larger cut in the barrier bar (Haines, 2006). With such large openings, more marine sand have could entered the lagoon during the inflowing tides during open phases, although this may have been mitigated somewhat by the lower sea levels in the past (Hannah, 2004). It appears that under a natural regime closed phases lasted longer than they do now. Open phases

possibly also lasted longer and the lagoon shifted less frequently between equilibrated marine and freshwater phases.

Ruppia is a natural component of the Waituna Lagoon ecosystem. It was present and appears to have been dominant under a natural opening regime. It is unclear how or when *Ruppia* was introduced to Waituna Lagoon. It has been hypothesized that *Ruppia* seeds were initially spread around East Asia by migratory birds (Ito *et al.*, 2010). The same method of introduction is plausible in Waituna Lagoon, which annually hosts many internationally and regionally migrating birds (Stevenson, 1986). Some of these birds may have stopped at lakes in Australia and/or East Asia which had abundant *Ruppia* beds, some of which lie on projected migratory routes. These birds probably also stopped at Te Waihora/Lake Ellesmere, a large lake further up the South Island's east coast which formerly had abundant *Ruppia* beds (Hughes *et al.* 1974). This possible method of continual reintroduction combined with the well-established seedbanks may have helped to maintain the presence of *Ruppia* in Waituna Lagoon.

In 1908 artificial management of the opening regime began, and the lagoon was opened more frequently than under the natural regime. The increased frequency of openings means conditions within the lagoon have become more estuarine, with little distinction between marine and freshwater phases recorded in the sediment. With rising sea levels (Hannah, 2004) and an eroding barrier bar (Kirk and Lauder, 2000) the system may be naturally developing from a lake to an estuary, with artificial management speeding up the process.

Under the artificial opening regime Waituna Lagoon has rapidly fluctuated between lake and estuarine conditions, with the upper 6 cm of sediment suggesting it has recently received more marine sand and possibly experienced more saline conditions. The water level has been maintained below the natural level to protect surrounding assets, resulting in a smaller hydraulic head during openings. Consequently the breaches of the barrier may have been smaller than they were naturally, probably resulting in more rapid closures and less marine sand input. Macrophyte beds probably became common throughout the lagoon, facilitated by a better light climate (Schallenberg and Tyrrell, 2006) due to the constrained maximum water levels. Thus, a number of key ecological characteristics of Waituna Lagoon are markedly different now than they were under a natural opening regime.

Macrophyte beds are currently threatened by high levels of nutrient enrichment, and there is concern that they will soon be eliminated from Waituna Lagoon (Environment

Southland, 2011). Unfortunately, it is precisely because of this nutrient enrichment that the continued dominance of *Ruppia* is so vital for the continued ecological viability of Waituna Lagoon (Hamill and MacGibbon, 2011).

The *Ruppia* pollen was not present in all samples, indicating that it may be able to endure through periods when flowering plants were absent, as was seen in Te Waihora/Lake Ellesmere after a period of decline (Gerbeaux, 1989). However this may have been an artifact of the small number of *Ruppia* pollen grains counted; and as was later seen in Te Waihora/Lake Ellesmere, macrophytes infrequently re-establish dominance after a switch to a phytoplankton-dominated state (Hamill and MacGibbon, 2011).

The Waituna Lagoon ecosystem was markedly different under a natural opening regime, and is being negatively impacted by anthropogenic activity. The results of this thesis should be helpful in determining restoration targets, if restoring the lagoon to its natural condition is desired.

7. References

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Appendix A. Detailed methodology and rationale

A.1 Sampling sites and core collection

Five cores were collected from Waituna Lagoon on 15 October 2009, eleven days after the lagoon barrier closed. The lagoon had been open since 29 July 2009 when the water level exceeded 2300 mm at the Waghorn Road bridge staff gauge, the normal level being 1200 mm. The lagoon closed naturally on 4 October 2009, and water levels were still low during sampling (Figs. 10 and 11).

Two sampling sites which were likely to have continuous records of sediment deposition were selected using a bathymetric map. One site was in Shand Bay, a sheltered embayment on the lagoons western edge (ca. 1 m water depth during sampling, Fig. 12), the other in the deepest area of a deposition basin in the eastern arm, near Hansens Bay (ca. 2.2 m depth). Shand Bay was sampled as it is sheltered and may be more buffered from direct marine influence, resulting in less sediment resuspension or removal.

Within these areas a metal probe was used to manually locate areas with deep water and soft sediment. Cores were collected beside these sites, to ensure the sediment had not been disturbed during site location. Sediment cores were collected using PVC drain pipes (inner diameter 70 mm, wall thickness 1.8 mm) and a push-coring method whereby the core tubes were driven vertically into the sediment until friction prevented further penetration. Cores were filled with water and capped with an airtight fitting before being carefully removed vertically from the lagoon bed. Core shortening and GPS locations were recorded prior to extraction. Cores remained upright and were stored at 5°C except during laboratory analysis.

Three cores were used as the basis of this study. Core I (Shand Bay; E2169949, N5395140) was the primary core for analysis, as it had the greatest length and the clearest x-ray density stratigraphy. Cores II (Shand Bay; E2169844, N5395165) and III (Eastern arm; E2174845, N5395175) were tested for a limited range of proxies to determine whether stratigraphic patterns were similar at the different sites in the lagoon (Table 3).

All analyses were completed at the University of Otago, and unless stated otherwise were completed in the Department of Zoology.

A.2 X-ray densitometry

X-ray densitometry was used to compare cores prior to extrusion, to determine which cores would be used in this study. Cores were x-rayed at the Dunedin Public Hospital Radiology Department prior to extrusion. The x-ray source was set to broad focus, 70 kv, 10 mAs (milliamperere-seconds, the quantity of x-rays reaching the film), at a distance of 1.53 m from the cores.

A.3 Sediment extrusion

The method of sediment extrusion varied between cores. Sediment from Core I was manually extruded, while Cores II and III were split lengthwise to facilitate analysis on the Geotek Multi-sensor Core Logger.

Core I was extruded without opening the core tube to reduce the risk of contamination between samples. The sediment was extruded by laying the core horizontally and using a plastic disc to push the intact sediment from the core onto a half-section of PVC drainpipe with the same diameter. The outer layer of the sediment was removed prior to sectioning the core into 1 cm slices, with care taken to avoid contamination between samples.

Cores II and III were split in half lengthwise. The plastic tubing was split using an angle grinder and the sediment divided with a thin wire. Angle grinders may result in core contamination by dragging sediment along the tube or spraying plastic swarf into the sediment (Weaver and Schultheiss, 1990). This may impact the percentages of water and organic material and the sediment grain size. To mitigate these potentially confounding factors the level of the blade was raised to prevent cutting the sediment and all swarf was carefully removed using tweezers. Where possible sediment was sub-sectioned from the centre of the core to further reduce the risk of contamination.

Visible sediment characteristics were logged for each core before sectioning into 1 cm slices. Core I was entirely sectioned, whereas only one half of Cores II and III were sectioned. The remaining halves were wrapped in plastic film and stored horizontally at 5°C for use on the Analyser. Sections from Core I were archived within acid-washed containers at 5°C; samples from the other cores were analysed immediately.

A.4 ^{210}Pb

Nineteen samples from Core I were analysed for ^{210}Pb by MyCore Ltd (Chalk River, Canada). The depths to be dated were determined by the pollen analysis, with the oldest *Pinus radiata* pollen grain serving as the tentative zone of transition for European influence on the lagoon. Five equidistant samples were selected below this horizon and ten above, with an additional four samples later analysed from the top 20 cm of sediment. One g (dry weight without gravel) of sediment was sent for analysis per sample.

^{210}Pb was measured by analyzing ^{210}Po , the granddaughter of ^{210}Pb . Samples were ground and weighed then known quantities of ^{209}Po , nitric and hydrochloric acids were added. Samples were heated at ca. 80°C for over 16 hours then centrifuged to separate residual siliceous solids. The samples were dried then rehydrated with a small quantity of HCl three times. Ascorbic acid and a small silver disc were added to each sample. The silver disc was covered on one surface with an adhesive to which the Po isotopes were electroplated.

Isotope dilution alpha spectroscopy was used to identify the alpha particles emitted by ^{209}Po and ^{210}Po . This system counted the particles for 0.25 to 2 days, depending on the level of ^{210}Pb activity in each sample. ^{210}Po activity was determined by the ratio of ^{209}Po to ^{210}Po , the sediment weight and the quantity of ^{209}Po added to the sediment.

A.5 Charcoal

Charcoal abundance was analysed in Core I. Charcoal is commonly counted on pollen slides during pollen analysis. Alternative methods were used due to concern over charcoal surviving the intensive digestive methods used to prepare pollen slides (Rhodes, 1998), and as the pollen method is qualitative. Charcoal was also counted during pollen analysis for comparison with these methods. The quantity of charcoal extracted per unit sediment using the following method was many magnitudes higher than the yield from the pollen analysis; therefore charcoal data presented in this study is from the following method.

Charcoal was prepared using a protocol developed by Rhodes (1998). This method minimizes charcoal fragmentation through reducing chemical and mechanical stresses

caused by other methods, and minimizes risks associated with mistakenly identifying other particles as charcoal by bleaching the organic material (Rhodes, 1998).

Samples of approximately 0.5 cm³ were taken at regular intervals, from the same depths as the pollen analysis. The sediment was air dried then 0.2 g of dry sediment was placed into Falcon tubes (Rhodes, 1998; Whitlock and Anderson, 2003). 20 ml of distilled water was added and the tubes were sealed and left for 24 hours to rehydrate. 5 ml of 30% hydrogen peroxide was added and gently mixed into the samples. This created a solution of 6% hydrogen peroxide, in which the samples soaked at 50°C for 48 hours.

The samples were filtered through Whatman Number 1 filter paper (pore size 2.5 µm) to remove the dark organic leachate. The filtrate was gently washed into petri dishes using milli-Q water, then dehydrated at 50°C until samples were air dried. Samples were weighed and rehydrated before charcoal fragments were counted. The second bleaching process used in Rhodes (1998) was not required.

Charcoal particles were counted using a macroscopic sieve (Whitlock and Anderson, 2003). Samples were sieved through nested metal sedimentology sieves, with mesh sizes of 90, 125 and 250 µm. Using milli-Q water, the sediment was gently washed through all sieves to separate charcoal grains into size classes. Charcoal from each sieve was washed into a large petri-dish, and then particles were counted into size classes under a dissecting microscope (10x magnification).

This method of size classification and counting was abandoned. Some charcoal particles adhered to the petri dishes and could not be removed without mechanical agitation, which may fragment the particles; and despite a rigorous cleaning of the sieves between samples particles remained trapped in the mesh. These factors negated the ability to quantify the charcoal content and posed a high risk for cross-contamination between samples.

To remove these confounding factors charcoal particles were manually counted within the original petri dishes without being sieved, using a 1 mm grid to ensure particles were only counted once. Particle sizes were not measured, but the results were more accurate as no charcoal was lost through sieving. All samples were analysed using this method. Rose (2004) found manual counts to be a highly effective method of counting charcoal when compared to computer-assisted counts.

Samples were counted under a dissecting microscope at ten times magnification. Immediately prior to counting the samples were gently moistened with milli-Q water using

a plastic pipette. This reduced the movement of grains and enhanced the lustre of charcoal particles.

A.6 Pollen

Pollen was analysed in Core I using a protocol developed from Fægri and Iversen (1975), Moore and Webb (1978), Jones and Cundill (1978), Vandergoes (2000) and Cadmus (2004). These authors used similar methods, but the publications included insufficient information for replication. Therefore they were used to develop the following protocol, which is relayed in detail to enable subsequent replication. The sub-sections are based upon divisions in Vandergoes (2000).

A.6.1 Sub-sampling

Pollen was analysed in 17 samples. Samples were selected at 10 cm intervals for sediment from 130 – 40 cm depth, and 5 cm intervals from 30 – 1 cm depth (inclusive). The additional upper samples were included to provide a higher resolution for inferring ages of sediment strata using indicator pollen. Cadmus (2004) found this “modern” horizon to be at 12.5 cm in Currans Creek, a tributary of Waituna Lagoon; and 19 cm depth in the Waituna wetlands. Two g of wet sediment was analysed from samples with high organic content, and 5 g from inorganic sediments.

A.6.2 Deflocculation

Samples were placed in 50 ml polypropylene Falcon tubes and soaked in 9 ml of 10% KOH for 18 hours. During this time the samples disaggregated and deflocculated.

Samples were boiled in a water bath for 20 minutes and mixed on a vortex for 30 seconds at 2000 rpm immediately before boiling and after 10 and 20 minutes in the water bath. Splashing sediment onto the inside of the lids was minimised to ensure all sediment was boiled. To prevent splashing, Falcon tubes were held firmly 2 cm below the lid during mixing, and samples dominated by silt and clay particles were mixed using a pulsing motion. The liquid level within each tube was checked immediately prior to mixing, and

milli-Q water added as necessary to prevent the KOH concentration exceeding 10%. Most samples received 3 ml of water after 10 minutes of boiling.

A.6.3 *Removal of extraneous matter*

After cooling, samples were wet sieved through a 125 μm metal sedimentology sieve using milli-Q water. Coarse particulate and organic matter was trapped in the sieve and stored for reference. The fine fraction including pollen was returned to the Falcon tubes.

Lycopodium marker tablets (Lund University) containing $13,500 \pm 3\%$ *Lycopodium* spores were added to determine the pollen extraction efficiency and to assist with the determination of pollen counts. The tablets were dissolved separately in 1 ml of 10% HCl. One tablet was added to each sample, and mixed by centrifuging for 3 minutes at 3000 rpm. This produced a pellet of debris at the bottom of the tube. The supernatant was decanted.

Two methods were used for decanting the supernatant: (1) the tube was tipped to a 90° angle in a single, flowing motion; or (2) a pipette was used to remove as much material as possible without making contact with the pellet. The second method was used when corrosive chemicals had been added and when the pellet was not very solid. If the pellet was disturbed the sample was centrifuged again to prevent decanting the pollen. Unless stated otherwise the supernatant was discarded.

A.6.4 *Removal of humic acid and calcium carbonate*

Seven ml of 10% HCl was added to each sample. Samples were then heated in a 50°C water bath for 5 minutes. Samples were cooled to room temperature then centrifuged for 3 minutes at 3000 rpm and the supernatant discarded. Eight ml of milli-Q water was added before centrifuging for 3 minutes at 3000 rpm and decanting. All waste was stored for appropriate disposal.

A.6.5 *Heavy liquid separation*

Zinc chloride was mixed to a specific gravity of 2.1 (Vandergoes, 2000). Ten ml of zinc chloride was added to each sample. Samples were mixed using a vortex mixer at 2500 rpm

for 1 minute or until no clumps remained, whichever was longer. It was necessary to completely break up the pellet as heavy liquid separation operates on the principle that pollen is lighter than the liquid and will float (Fægri and Iversen, 1975).

The samples stood for 30 minutes to allow separation of the heavy and light fractions then were centrifuged for 10 minutes at 2000 rpm. Care was taken not to mix the heavy and light layers. The zinc chloride, containing the light fraction, was decanted into a beaker of 105 ml milli-Q water. The water diluted the zinc in the sample to a specific gravity of ca. 1.

The heavy fraction was stored within the Falcon tubes for reference. For each sample 35 ml of the light fraction of was placed into a new Falcon tube. The tubes were centrifuged for 10 minutes at 2000 rpm and the supernatant decanted into a chemical waste bottle. This step was repeated until each 115 ml sample formed a pellet within a single Falcon tube.

A.6.6 Acetolysis

Acetolysis was completed to remove plant cellulose. All steps were conducted within a fume cupboard due to the highly corrosive chemicals being used. Only two samples were prepared at a time to minimise the time they spent in the acid solutions.

Samples were dehydrated by adding 5 ml of concentrated glacial acetic acid, then mixed on the vortex at 2000 rpm for 10 seconds or until the pellet was completely disaggregated, whichever was longer. They were centrifuged at 3000 rpm for 3 minutes and the supernatant decanted.

To each sample 6 ml of 9:1 acetic anhydride : sulphuric acid was added. Samples were mixed on the vortex at 2000 rpm for 10 seconds or until the pellet was completely disaggregated, whichever was longer. They were then placed in a boiling water bath for 2 minutes. Once the samples had cooled completely they were centrifuged at 2000 rpm for 4 minutes and the supernatant decanted.

Samples were washed in 7.5 ml of milli-Q water. They were mixed on the vortex for 10 - 30 seconds at 2000 rpm, centrifuged for 3 minutes at 3000 rpm and the supernatant decanted. Finally, samples were washed in 5 ml of 10% KOH, mixed on the vortex for 10 seconds at 2000 rpm, centrifuged for 3 minutes at 3000 rpm and the supernatant decanted. All waste was collected and stored for appropriate disposal.

A.6.7 Staining and slide preparation

Pollen grains were stained with basic fuchsin for ease of identification. The stain was prepared under a fume hood. One g of basic fuchsin was added to 50 ml of 40% acetic acid. The solution was heated to 50°C to dissolve the fuchsin, then cooled to 30°C and filtered through filter paper.

Two drops of fuchsin was added to each sample. Samples were mixed on the vortex for 20 seconds at 2200 rpm then centrifuged for three minutes at 3000 rpm. The supernatant was decanted. Excess stain was removed by washing the samples in 10 ml of milli-Q water. Samples were mixed on the vortex for 20 seconds at 2200 rpm, centrifuged for three minutes at 3000 rpm and the supernatant decanted. This was repeated until the supernatant was clear, ca. 5 - 6 times per sample.

The pollen was mounted on slides in glycerine jelly. Six drops of molten glycerol was added to one drop of residue and mixed thoroughly. One drop of this solution was added to each pre-labelled slide and a cover slip added. Slides were left on a warming tray for the glycerol to set, then sealed with clear nail varnish. At least one duplicate was made of each slide, and the remaining pollen was refrigerated for further reference.

A.6.8 Counting and identification

Pollen was identified using a compound microscope at 40x magnification. Dimbleby (1957) suggested that a minimum of 250 grains be counted per sample to ensure representation of all major taxa. Not all species could be identified in this study due to time constraints. Instead, priority was placed upon identifying species which are indicative of land use changes including natural and anthropogenic disturbance, and species which are important for answering the hypotheses (section 3.6; Figs. 29 and 30).

Each sample was counted until 250 grains of these “indicator species” (below) had been identified. Where this was not possible, counting continued until at least 300 *Lycopodium* spores were counted. All pollen grains were counted. Broken grains where more than 60% remained were included, and separated into pollen which may have belonged to indicator species, and pollen which clearly did not. Guides used for identification include Erdtman (1952, 1969), Moore *et al.* (1991) and Raine *et al.* (2005).

Dacrycarpus dacrydioides (kahikatea), *Dacrydium cupressinum* (rimu), *Pinus radiata* (Monterey pine) and *Weinmannia racemosa* (kāmahi) were identified to assist with dating. Podocarp forest was widespread around Waituna when Europeans began permanent settlement of the district (Floyd, 1980). While land was being converted into pasture logging this forest was the dominant occupation (Floyd, 1980). *D. dacrydioides*, *D. cupressinum* and *W. racemosa* were all components of the pre-European and modern forested areas around Waituna. Their abundance is expected to change shortly after European settlement. *P. radiata* is an exotic species which was planted locally by European settlers and is commonly used as an indicator of European settlement (Hicks and Nichol, 2007; section 2.3.1).

Leptospermum scoparium (mānuka) and *Pteridium esculentum* (bracken fern) form two of six major vegetation types at Awarua Bog, which borders the western edge of Waituna Lagoon (Johnson, 2001). They were identified in this study as they are prolific early successional colonisers after terrestrial disturbance, particularly fire (Johnson, 2001). The patterns of abundance of these species may be used to infer dates of sediment deposition as large fires have been recorded in local history. Such disturbance events often affect standing water bodies by causing rapid sedimentation (McFadgen and Goff, 2005), so the abundance of these species may be useful for distinguishing between changes due to terrestrial disturbance and the opening regime. In addition, *P. esculentum* is closely associated with human activity and often increased after Māori settlement, for which it has often been used to infer dates (McGlone *et al.*, 2005; section 2.3.1).

The macrophytes *Myriophyllum triphyllum* (water milfoil), *Ruppia megacarpa* (large-fruit tassel) and *R. polycarpa* (horse's mane weed) were identified. These three species are the most dominant macrophyte species within Waituna Lagoon, and have been for at least the last decade (Johnson and Partridge, 1998; Thompson and Ryder, 2003; Stevens and Robertson, 2007; Robertson and Stevens, 2009). The *Ruppia* species are crucial for answering two of the hypotheses. The pollen of *R. megacarpa* and *R. polycarpa* could not reliably be distinguished from one another, so *Ruppia* was identified to genus. This is satisfactory as it is the presence of the genus and not the individual species which is important for this study.

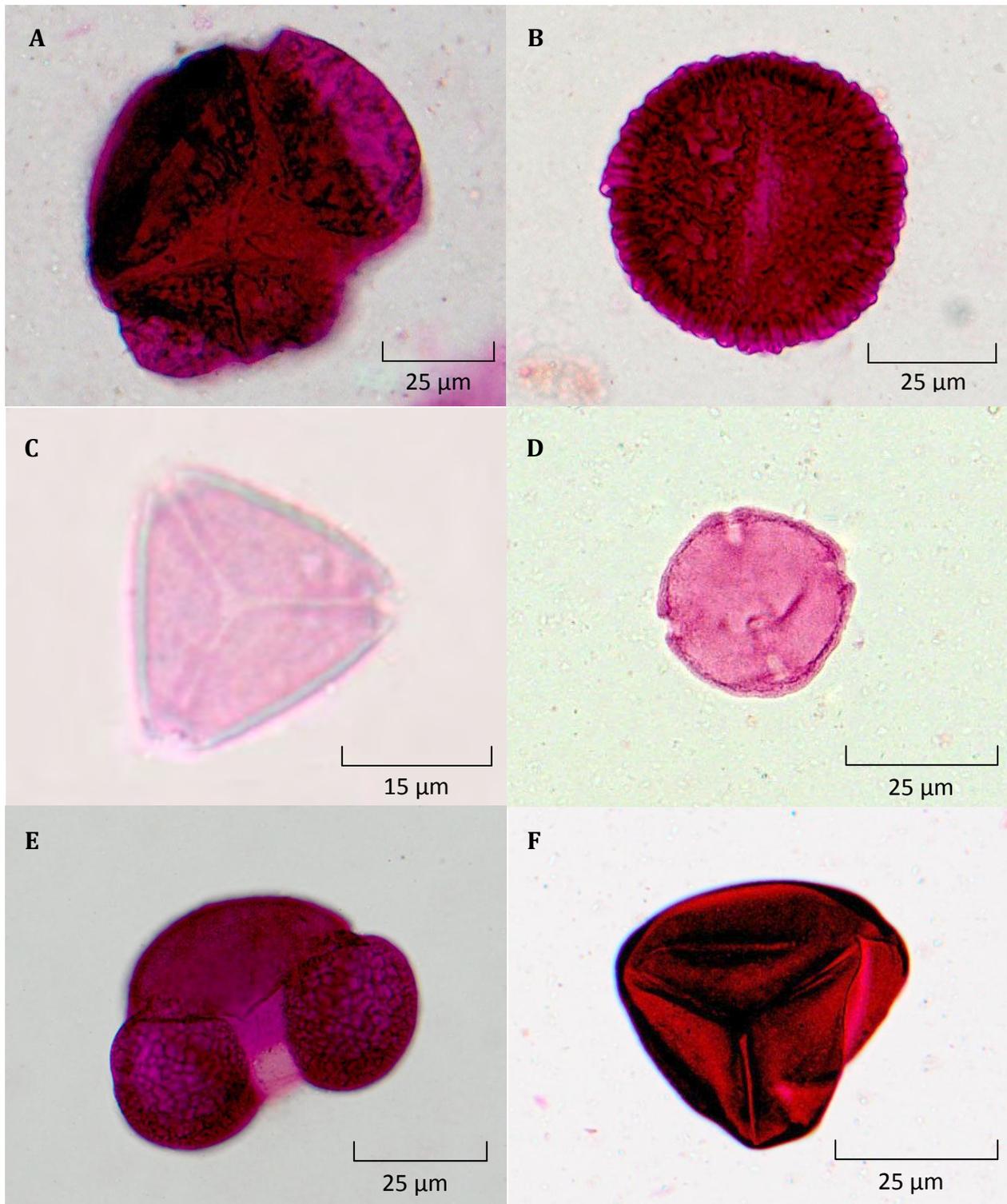


Figure 29: Examples of indicator pollen grains from the top 10 cm of Core I from Waituna Lagoon. In some cases undamaged grains were unavailable. A – *Dacrycarpus dacrydioides*, B – *Dacrydium cupressinum*, C – *Leptospermum scoparium*, D – *Myriophyllum triphyllum*, E – *Pinus radiata*, F – *Pteridium esculentum*

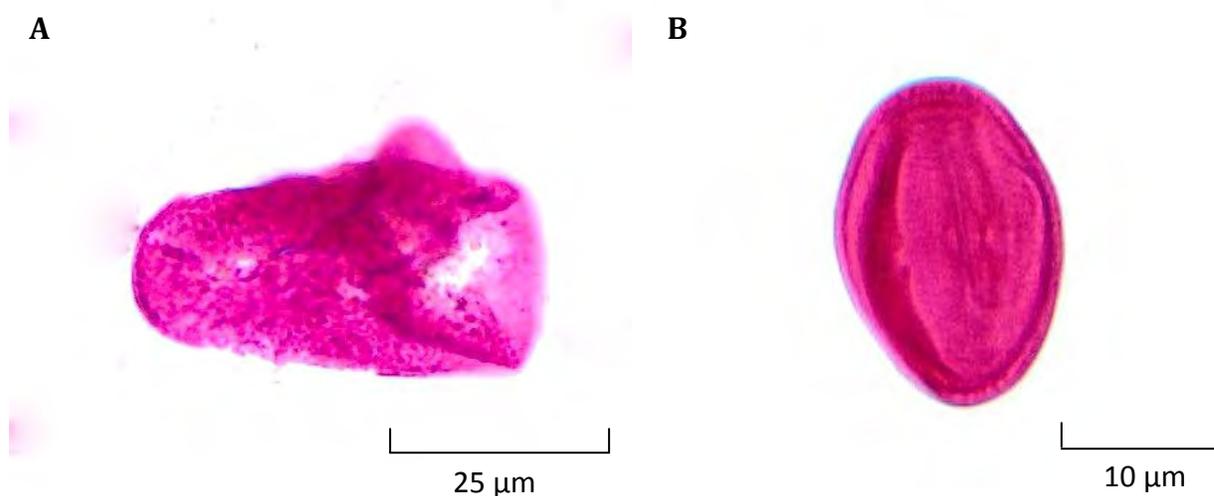


Figure 30: Examples of indicator pollen grains from the top 10 cm of Core I from Waituna Lagoon. In some cases undamaged grains were unavailable. A – a folded *Ruppia* pollen grain, B – *Weinmannia racemosa*

A.7 Foraminifera

Foraminifera were extracted with macrofossils from Core III (Appendix A.8.1) and through a targeted method from Core I which is described below. Foraminifera extraction was completed at 1 cm intervals for sediment from 130 - 101 cm depth, in an attempt to reconstruct the natural opening regime.

Samples were dried in a warming oven at 60°C for 48 hours then 20 g of sediment subsampled for foraminifera extraction. Drying the samples posed a risk of losing thin-walled agglutinated foraminifera; however there were advantages in using this method and calcareous foraminifera should have been unaffected (Hayward *et al.*, 2007).

Following drying and weighing, samples were tested under a dissecting microscope for calcareous matter by adding two drops of 5% HCl to check for fizzing. No samples fizzed upon contact with HCl. Samples were then examined for calcareous and agglutinated foraminifera, ostracods, fossils, shell fragments and diatoms under a dissecting microscope at 4x and 10x magnification. The sediment was gently crushed between two clean sheets of paper to break clumps, then wet sieved through a 63 μm metal sedimentology sieve for 30 seconds or until the water ran clear, whichever took longer. To ensure there was no cross-contamination the sieve was rinsed in methylene blue and washed between samples.

Samples were checked for foraminifera under a dissecting microscope at 10x magnification before and after drying the sediment under a heat lamp for 24 hours. Samples were dry sieved through a 500 μm metal sedimentology sieve, which was cleaned by blasting with high pressure air. The coarse and dry fractions were weighed. The coarse fraction was checked for foraminifera under a dissecting microscope at 10x magnification then stored for reference. The remainder of the method analysed the fine fraction.

The fine fraction was emptied into a small ceramic bowl. 300 ml of chloroform was added and the sample was suspended by stirring with a glass rod. The particles which floated were filtered through a Whatman Number 3, 18.5 cm qualitative filter paper. The process was repeated then the heavy fraction remaining in the ceramic bowl was dried and stored. The light fraction sitting on the filter paper was suspended in ethanol and analysed with a dissecting microscope at 10x magnification. Caution was taken not to sharply disturb the air around the sample to prevent the particles blowing away.

Samples were suspended in ethanol to break aggregates, with foraminifera removed using a fine brush and glued to a sorting tray for subsequent counting. This last stage of manual extraction was completed under a dissecting microscope of 10x magnification, with each sample analysed for three hours to ensure equal sampling effort and the extraction of all foraminifera.

A.8 Macrofossils

A.8.1 Macrofossils of 355 – 3000 μm diameter

The sediment from 130 – 80 cm depth of Core I and all of Core III were examined for macrofossils of 355 - 3000 μm diameter. At 1 cm intervals samples were weighed then wet sieved through nested metal sedimentology sieves of 355 and 3000 μm . The material trapped between the sieves was sorted using a dissecting microscope at 4x magnification.

In Core I the focus was on finding material for ^{14}C dating, which was unsuccessful. All macrofossils in Core III were counted and identified (Fig. 31) in consultation with the following experts and published guides: ephippia - M. Schallenberg from the University of Otago; foraminifera – D. Lee and E. Fordyce from the University of Otago, and Hayward and Hollis, 1994 (see Appendix C.1); seeds – B. Clarkson, B. Lee, J. Wood and P. Johnson from

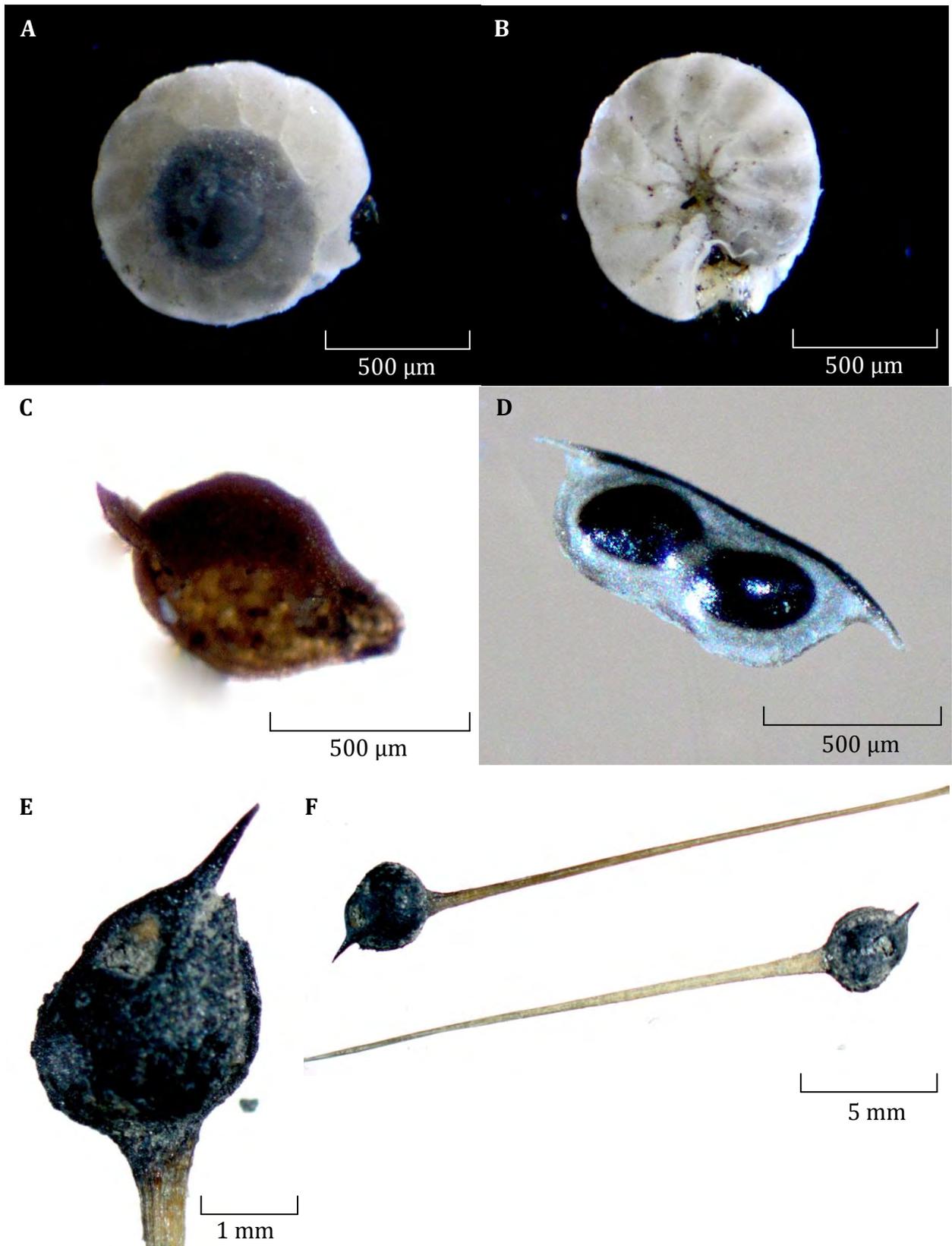


Figure 31: Macrofossils extracted from Core III from the Eastern arm of Waituna Lagoon. A – dorsal view of *Ammonia beccarii*, B – ventral view of *Ammonia beccarii*, C – *Baumea tenax* seed, D – *Daphnia ephippia*, E – head of a *Ruppia* seed, F – *Ruppia* seeds

Landcare Research and Webb and Simpson, 2001.

Representatives of the snail groups were coded and catalogued for subsequent identification. When identifying the snails a large phenotypic diversity (primarily colouration) was discovered which had not been visible at the lower resolution used for counting. The majority of snails were *Potamopyrgus antipodarium* but accurate identification of all species was not possible. Consequently snails were grouped into a single unit.

A.8.2 Macrofossils larger than 3000 µm diameter

All cores were tested for macrofossils larger than 3000 µm diameter at 1 cm intervals. The 3000 µm mesh size was selected to ensure extraction of all *Ruppia* seeds. Samples were weighed then wet sieved, with all macrofossils removed, counted and identified using Johnson and Brooke (1989; Fig. 31). This analysis was completed last to prevent contamination of more sensitive analyses. Sediment sub-sampled for previous analyses were checked for *Ruppia* seeds prior to analysis.

Appendix B. Additional results

B.1 Core imaging

Images of Cores II (Shand Bay) and III (Eastern arm) were captured using the Geotek Multi-Sensor Core Logger (Fig. 32).

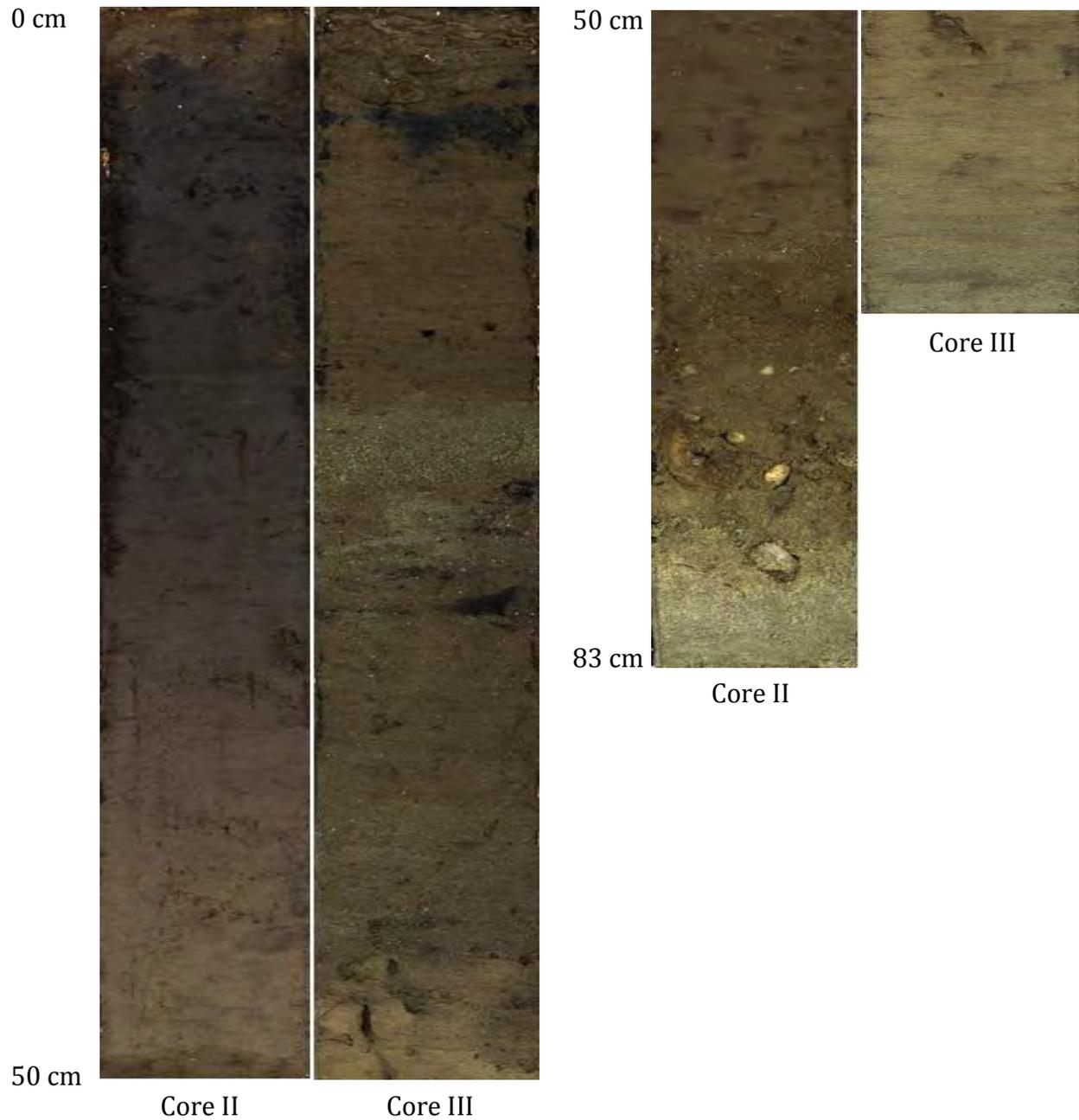


Figure 32: Images of Cores II (Shand Bay) and III (Eastern arm) from Waituna Lagoon

B.2 ²¹⁰Pb

The ²¹⁰Pb data and a projected dating model for Core I from MyCore Ltd are presented in Table 10.

Table 10: ²¹⁰Pb data and projected dating model provided by MyCore Ltd for Core I (Shand Bay), Waituna Lagoon. CRS = Constant Rate of Supply; SAR = Sediment Accumulation Rate; STD = Standard Deviation; CV = Coefficient of Variance

Depth (cm)	²¹⁰ Pb (Bq/g)	Precision 1 STD (%)	Age (year)	CRS SAR (g/m ² /yr)	CV in SAR (%)	STD in years
1	0.016	8.9	2009.9	16296	25	0
2	0.014	7.7	2008.9	19917	28	0
3	-	-	2008.1	27792	Interpolated	-
4	0.008	11.2	2006.4	46323	67	2
5	-	-	2006.2	37646	Interpolated	-
6	0.010	8.8	2006.0	31674	46	2
10	0.011	11.0	2004.9	25493	43	2
11	-	-	2004.6	39999	Interpolated	-
21	0.006	7.7	2002.5	90042	131	10
22	-	-	2002.4	70746	Interpolated	-
33	0.007	7.7	2000.9	55714	86	8
34	-	-	2000.7	61069	Interpolated	-
45	0.007	8.8	1998	62920	107	13
46	-	-	1998	72433	Interpolated	-
56	0.006	10.0	1995	79339	149	22
57	-	-	1995	79339	149	22
68	0.006	17.1	1992	87556	202	35
69	-	-	1992	Slump	N/A	-
75	0.005	33.7	1991	Slump	N/A	-
76	-	-	1991	23341	45	8
82	0.013	9.9	1986	10196	32	7

Depth (cm)	²¹⁰ Pb (Bq/g)	Precision 1 STD (%)	Age (year)	CRS SAR (g/m ² /yr)	CV in SAR (%)	STD in years
83	-	-	1985	15545	Interpolated	-
88	0.007	11.7	1979	32233	105	32
89	-	-	1979	14408	Interpolated	-
95	0.012	10.2	1973	7685	35	13
96	-	-	1971	8473	Interpolated	-
101	0.010	10.6	1960	7129	46	23
102	-	-	1957	6724	Interpolated	-
108	0.010	9.4	1931	3046	47	37
109	-	-	1923	3694	Interpolated	-
115	0.006	13.8	-	-	-	-
121	0.004	12.1	-	-	Background	-
128	0.003	23.0	-	-	-	-

The MyCore Ltd interpretation of the above table is as follows. The references to columns have been adjusted to match Table 10:

[Table 10] contains the Pb-210 concentrations [Column 2] expressed in Bq/g. This is units of Bequerels per gram. A Bequerel is defined as a disintegration per second. The concentrations in the Waituna core are very low. The highest concentrations are less than the background values in many lakes.

The precision in the measurement [Column 3] is expressed as a standard deviation. This includes all of the measurement uncertainty including those in weighing, radiochemical extraction and radionuclide counting. In your data the concentrations were very low. Even after counting each sample for >4 days we only collected a few counts and so the measurement uncertainty is limited by the counting statistics. As a result the results must be interpreted as overall trends since the uncertainty in a single value is large relative to the age or accumulation rate.

The age of each section in the core [Column 4] is expressed in years. It uses a reference of the date that the core was collected for the top of the core. The age that is calculated is the age at the top of each section. In sections where the Pb-210 concentration was not measured, the age is interpolated using linear interpolation of the Pb-210 concentrations.

The precision in the age estimate [Column 7] is expressed as a standard deviation in years. This value propagates all uncertainties in quadrature to determine the total uncertainty in the model calculation. In sections where data

are interpolated (ie the Pb-210 was not measured in that section), no uncertainty can be accurately estimated and so the entry in this column says 'interpolated' rather than provide an estimate of the uncertainty.

The sediment accumulation [Column 5] is expressed in grams dry weight per meter squared per year. This is the average for the section of the core. Your values are very high and reflect rapid deposition in a dynamic environment. Note that one area indicates a slump or very rapid burst(s) of sediment input due to the very low water content and the background concentration of Pb-210.

The precision in the SAR estimate [Column 6] is expressed as a coefficient of variation (in %). This value propagates all uncertainties in quadrature to determine the total uncertainty in the model calculation. In sections where data are interpolated (ie the Pb-210 was not measured), no uncertainty can be estimated accurately and the value is listed as not available (interpolated).

The Pb-210 concentrations were interpreted using the constant rate of supply (CRS) model of Pb-210 accumulation. In this model Pb-210 concentrations change due to radioactive decay (Aging) and changes in sediment accumulation rate. If the rate of sediment accumulation is constant, then the Pb-210 concentration declines with depth in a simple exponential series.

The uncertainty in the sediment accumulation rate and in the age of the section both increase deeper in the cores. This is not the result of an analytical or laboratory procedure. It is the result of the smaller and smaller difference between the measured Pb-210 concentration and the background concentration as we move farther down the core.

The uncertainties in the dates and in the sediment accumulation rates are very large (e.g. >25% and 25 years) when there is a small excess of Pb-210 above the background. This occurs when the Pb-210 concentration is less than 2 times greater than background and for most of the depth of your core this is the case.

The length (or # of sections) in a core that can be dated is determined by the amount of Pb-210 input from the atmosphere and the background concentration of Pb-210 contributed by the *in situ* decay of Pb-210 in the sediment. The latter is controlled by the geology of the area and the amount of uranium and radium in the rocks and soils in the catchment. Your core has a very low background (good news) but also low inputs of Pb-210 from the atmosphere and this is what limits the dating and uncertainty in the analysis.

Following discussion with MyCore Ltd., it was determined that the levels of ^{210}Pb in this core were too low to use them to accurately ascribe dates to depths. As a result the ^{210}Pb data was not used for interpretations in this study.

No material suitable for ^{14}C dating was found in Core I during the extraction of macrofossils, and bulk dating of sediments was not attempted due to the high rate of error it is associated with.

B.3 Geotek Multi-Sensor Core Logger

The Geotek Multi-Sensor Core Logger was used to analyse Cores II and III. It created high resolution colour images of the cores and measured the electrical resistivity (salinity), gamma-ray attenuation (bulk density), magnetic susceptibility and average reflectance. From these analyses, only the colour images were useful for the present study. A correlation matrix comparing results from the Analyser with other variables is presented in Table 11.

Table 11: Correlations between select results from the Geotek Analyser and other analyses at Waituna Lagoon using all cores. From Shand Bay the organic material, resistivity and density data was generated from Core II, all other variables were tested in Core I. The units used for analysis are as follows: electrical resistivity = Ohm.m; depth = cm; water = percentage of the sediment; sand, silt and organic material = percentage of dry sediment; bulk density = g/ml; grain size = geometric mean grain size. “ns” indicates the *P* value was not significant at $\alpha = 0.05$

Variable	Shand Bay (Cores I and II)			Eastern arm (Core III)		
	<i>R</i> ² value	<i>P</i> value	Direction	<i>R</i> ² value	<i>P</i> value	Direction
Resistivity vs depth	0.644	< 0.001	Positive	0.860	< 0.001	Positive
Resistivity vs organic	0.480	< 0.001	Negative	0.343	< 0.001	Negative
Resistivity vs water	0.410	< 0.001	Negative	0.552	< 0.001	Negative
Resistivity vs silt	0.145	< 0.001	Negative	0.005	ns	-
Resistivity vs sand	0.192	< 0.001	Positive	0.028	ns	-
Density vs depth	0.859	< 0.001	Positive	0.564	< 0.001	Negative
Density vs water	0.702	< 0.001	Positive	0.771	< 0.001	Negative
Density vs grain size	0.112	0.001	Positive	0.092	0.016	Positive

Electrical resistivity was not used in this study as the data did not fit with the known opening regime. Prior to this study it was known that Waituna Lagoon goes through periods of opening and closure. Therefore it was expected that periods with high sand and low organic content in the sediment would indicate the lagoon was open. This trend was supported using a range of proxies (section 5.2) but the opposite trend was seen using the electrical resistivity (Fig. 33). Resistivity was significantly correlated to the quantities of organic material, silt and sand in the sediment, all indicators of the opening regime, but in

the opposite direction to what was expected (Table 11). The electrical resistivity data suggested that salinity decreased as the percentage of sand increased, and vice versa (Fig. 33). This data was counter-intuitive and conflicted with other data gathered; therefore it was not included in the results. Salinity variations may be masked by depth and water content in this system (Table 11).

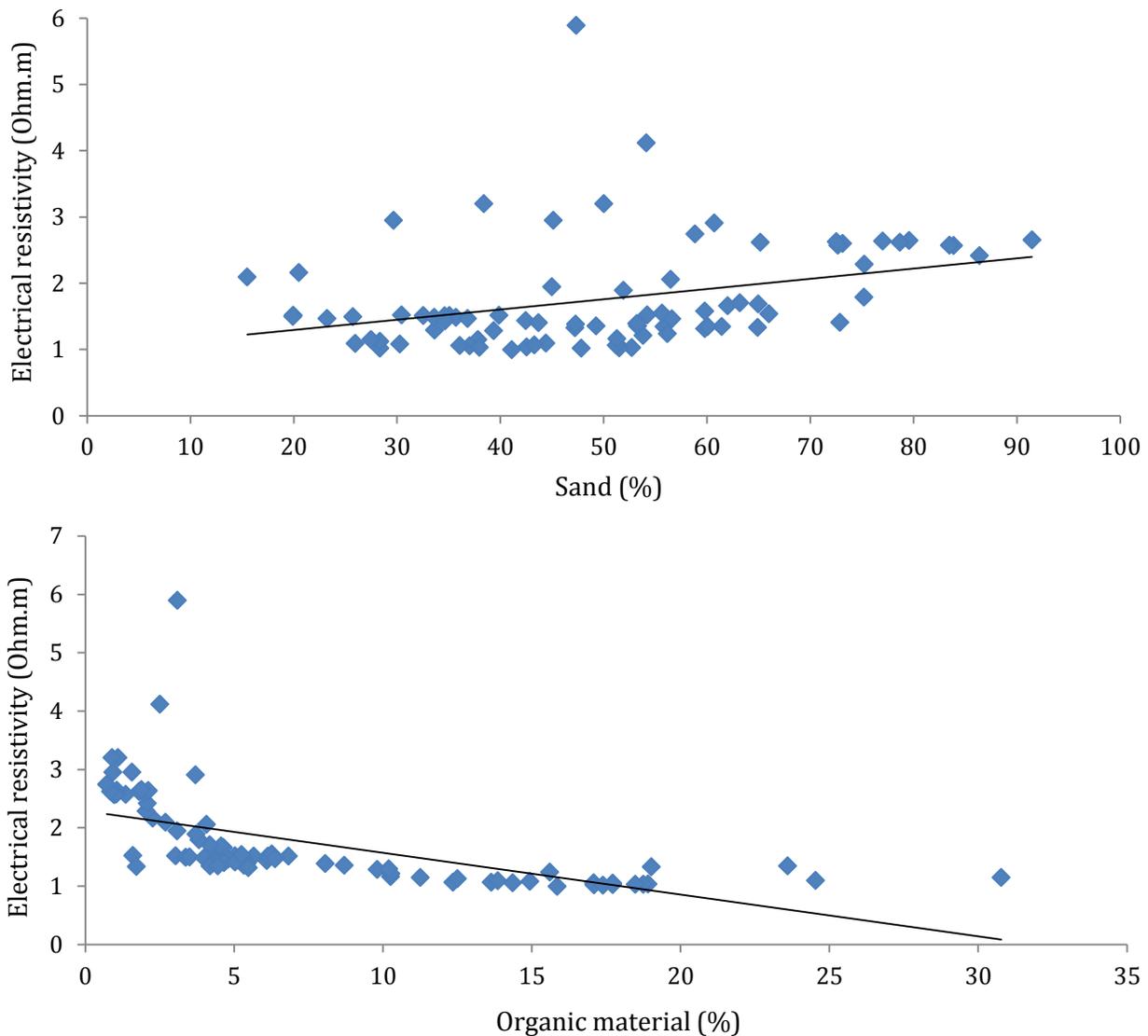


Figure 33: The correlations between electrical resistivity (Core II) versus and sand and organic material (Core I), Shand Bay, Waituna Lagoon

Electrical resistivity may not be indicative of salinity in systems where the physical characteristics of the sediments change markedly. It also may not be useful in relatively modern sediments, such as those analysed in this study.

Gamma-ray attenuation (bulk density) was significantly correlated with the depth, water content and geometric mean grain size of the sediment. This data was not used in the present study as it did not contribute to answering any of the hypotheses, and without a sediment chronology available it is not known whether these correlations were artifacts of sediment compression over time. The trend was also different between sites, possibly reflecting the different deposition environments.

The average reflectance and magnetic susceptibility data were not used in the present study as it did not advance an understanding of trends related to the hypotheses.

B.4 Pollen

The pollen retention rate was calculated using *Lycopodium* spores, as the number of *Lycopodium* spores divided by the total count of whole pollen grains. This was converted to a percentage and then subtracted from 100, to give the retention rate of the pollen from the sediment. Samples in the lower half of the core had the lowest retention rates. The highest pollen retention was 99.2% at 30 cm, and the lowest 2.3% at 130 cm.

In total 48,883 pollen grains were counted, including 3,102 from indicator species, 25,984 from other species, 17,688 broken grains (13,878 of which were clearly not from indicator species). Broken grains comprised 36.2% of the total count (excluding grains which had 60% or less remaining, which were not counted to avoid a potential overestimation of pollen abundance). Of the unbroken pollen grains only 11.9% belonged to the eight indicator species.

As stated in the methodology (section 4.8, Appendix A.6.8), each sample was counted until 250 grains of indicator species or 300 *Lycopodium* spores were counted and identified. As a result of this method, the total pollen count excluding *Lycopodium* ranged from 29 (130 cm) to 9,988 grains (40 cm; Table 12), allowing data standardization to counting effort (section 4.11). In three samples the benchmark of 300 *Lycopodium* spores was reached before sufficient indicator species had been counted. These samples were from 70 cm ($N = 16$ indicator species), 120 cm ($N = 3$) and 130 cm ($N = 0$).

Table 12: Pollen results from Core I (Shand Bay), Waituna Lagoon. Key: A – *Dacrycarpus dacrydioides*, B – *Dacrydium cupressinum*, C – *Leptospermum scoparium*, D – *Myriophyllum triphyllum*, E – *Pinus radiata*, F – *Pteridium esculentum*, G – *Ruppia*, H – *Weinmannia racemosa*

Sample (cm)	Indicator species (% total count)								Total count			
	A	B	C	D	E	F	G	H	Indicator spp. (%)	Broken (%)	Total whole	
1	1.9	2.7	2.7	0.5	14.2	10.9	0.5	0.5	38.4	27.8	1083	
5	0.4	0.3	0.3	0.0	2.5	28.9	0.1	1.8	53	35.1	727	
10	0.0	0.3	0.5	0.0	0.3	33.0	0.0	3.6	49.4	23.8	664	
15	0.0	1.0	1.7	0.0	0.2	38.5	0.0	0.0	41.3	42.0	1044	
20	0.0	0.7	0.4	0.5	0.1	13.7	0.0	0.0	24.1	36.4	1904	
25	0.3	1.2	1.5	0.6	0.3	4.0	0.2	0.5	8.8	31.6	4170	
30	0.0	0.3	0.3	0.3	0.0	4.1	0.0	0.1	7.5	32.9	4973	
40	0.0	0.1	0.4	0.1	0.1	0.7	0.1	1.1	4.2	40.5	9988	
50	0.0	0.1	0.3	0.1	0.1	0.7	0.2	0.7	4.5	51.3	4916	
60	0.0	0.0	0.4	0.2	0.0	0.6	0.4	3.0	7.7	40.6	2147	
70	0.0	0.0	2.3	0.0	0.0	1.4	0.5	3.3	12.1	38.0	213	
80	0.0	0.0	0.0	0.1	0.0	0.1	0.2	5.1	7.2	24.1	4559	
90	0.0	0.0	0.0	0.1	0.0	0.0	0.1	4.4	8.5	44.7	5343	
100	0.0	0.0	0.1	0.2	0.0	0.1	0.1	6.2	9.5	30.7	3800	
110	0.0	0.0	0.1	0.2	0.0	0.5	0.0	2.5	7.3	55.6	1103	
120	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.7	8.8	69.4	111	
130	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	79.3	29	
Average	0.2	0.4	0.6	0.2	1.0	8.1	0.1	2.1	17.2	41.4	2751.4	
											Total	46,774

The data from 70 cm was not excluded from the dataset as four of the eight indicator species were observed, providing useful information. At 120 cm the only indicator pollen grains counted were three grains from *Weinmannia racemosa*, with 31 grains from non-indicator species and 77 broken grains. At 130 cm depth the total pollen count was only 6 grains from non-indicator species and 23 broken grains. The samples at 120 and 130 cm depths had the highest percentage of broken pollen (69.4% and 79.3% respectively). The very low number of pollen grains found at these depths prevented a reliable interpretation of the pollen record at these depths, and resulted in these samples being excluded from the dataset.

B.5 Macrofossils

Nine distinct taxa were extracted during the analysis of macrofossils in Core III (Eastern arm). Four taxa had a very low abundance, with only 2 – 6 seeds present in the 63 cm core. Three of these taxa were only present at 43 cm depth. As these species had very low abundances and were not ecologically informative they are not discussed further. All taxa except *Daphnia ephippia* were found at 43 cm, and their abundance peaked between 43 - 39 cm depth.

The most informative seeds extracted were *Ruppia* and *Baumea tenax*. Only five *Ruppia* seeds were found, occurring at 35 - 33 cm (section 6.3). Seeds from the sedge *B. tenax* were found throughout the core ($N = 69$) and were most abundant in deeper sediment (Fig. 34).

Snails were not identified to a high resolution (Appendix A.8.1). Twenty-one snails were found, with a relatively even distribution (Fig. 34). The highest densities were achieved at 39 cm ($N = 5$) and 41 cm ($N = 4$). The brackish-water foraminifer *Ammonia beccarii* was found at a high abundance, with 5,383 specimens in the core, giving an average density of 437 specimens per cm^3 . It was most abundant in the mid to lower sections of the core, with the highest abundance at 40 cm ($N = 1,071$; Fig. 34). It was significantly negatively correlated with the percentage of organic material ($P = 0.010$, $R^2 = 0.101$), strengthening the inferred correlation of high levels of organic material and the lagoon being closed. *Daphnia ephippia* were also found throughout the core, but at a much lower abundance ($N = 12$). It was most abundant in the upper 20 cm (Fig. 34), and was not significantly correlated with any indicators of the opening regime.

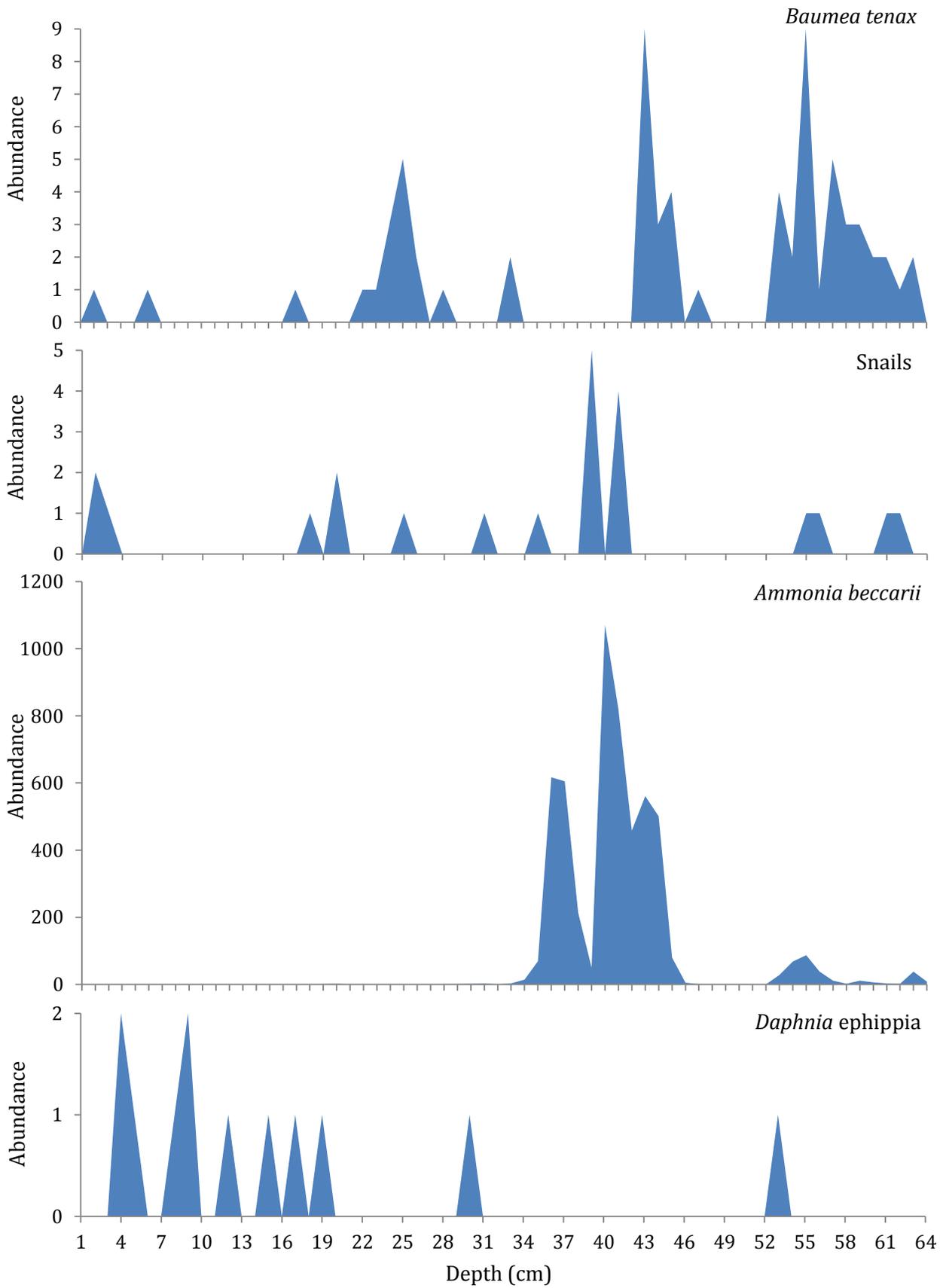


Figure 34: Macrofossils found in Core III from the Eastern arm of Waituna Lagoon

Appendix C. Ecology of taxa found at Waituna Lagoon

This appendix details the ecology of select taxa found at Waituna Lagoon during this study. *Baumea tenax* is included as its seeds were abundant in Core III. All other taxa were informative about conditions at the time of deposition. This does not attempt to be a comprehensive list of species found in Waituna Lagoon and wetlands (see Thompson and Ryder, 2003), and does not include microfossils present in very few samples.

C.1 *Ammonia beccarii*

Ammonia beccarii (Rotaliidae) is a species of foraminifera which has been found in temperate regions around the world (Muller, 1975). The “most consistently occurring” calcareous foraminifer in New Zealand, *A. beccarii* has been recorded in brackish environments throughout New Zealand including Auckland and Stewart Island (Hayward and Hollis, 1994).

A. beccarii is a euryhaline species which lives on tidal flats and in intertidal and subtidal environments (Hayward and Hollis, 1994; Hayward *et al.*, 1997). It is highly abundant in estuarine environments, wherein it occurs in areas with high salinity (Hayward and Hollis, 1994) and reaches the highest densities in sandy environments (Debenay and Guillou, 2002), though it tolerates a broad range of sediment grain sizes (Hayward *et al.*, 1997).

Although the foraminifera found at Waituna Lagoon could be identified as belonging to the genus *Ammonia* with little difficulty, identification to a species level was much more challenging due to the highly confused nomenclature. It was identified as *Ammonia beccarii*, and based on Hayward and Hollis (1994) it is probably *Ammonia beccarii* forma *aoteana*. Because of the confused nomenclature it is an international convention to use a broad definition of *A. beccarii* (Holzmann, 2000) and due to a lack of live tissue for rDNA analysis that convention is followed here. This convention has compounded the problem with a broad range of morphologies now identified as a single species (Hayward *et al.*, 2004b), but until the taxonomy has been formally revised a more accurate identification will not be possible.

C.2 *Dacrycarpus dacrydioides* (kahikatea; New Zealand white pine)

Dacrycarpus dacrydioides (Podocarpaceae) is the tallest forest tree indigenous to New Zealand, growing up to 60 m tall (Riley, 2004). It inhabits swamp land, frequently forming and dominating swamp forest (Dawson and Lucas, 2000), and can also be found on dry hills from sea level to 2000 feet (Richards, 1949). Before human settlement many fertile lowland regions in the North Island and South Island were covered with almost pure forests of *D. dacrydioides* (Robertson and Hackwell, 1995). As a result of land use changes and forestry (Riley, 2004) this forest type has been greatly restricted, with only an estimated 2% of the original swamp forests remaining (Cometti, 2008). *D. dacrydioides* can still be found throughout the three main islands of New Zealand in lowland and hilly regions, and often dominates remaining swamp forest (Robertson and Hackwell, 1995; Foster, 2008).

Relatively shade intolerant, *D. dacrydioides* forms an upper forest canopy (Smale *et al.*, 2005). Its main method of recruitment is mass succession after disturbance (Smale *et al.*, 2005), and in relatively unmodified native podocarp forests of south Westland, New Zealand, *D. dacrydioides* is one of the dominant forest trees in areas with frequent flooding (Duncan, 1993). Duncan (1993) found that in areas without sufficient flooding events *D. dacrydioides* is replaced by *Dacrydium cupressinum*.

To Māori, *D. dacrydioides* is one of the most sacred trees in New Zealand (Foster, 2008). The red, fleshy fruit (“koroi”) and the birdlife which it attracted were eaten, the timber was used for canoes (“waka”), the resin was chewed and the leaves were used for medicine (Richards, 1949; Foster, 2008). It is currently used as a forestry species for the timber which it produces (Riley, 2004).

C.3 *Dacrydium cupressinum* (rimu; red pine)

Dacrydium cupressinum (Podocarpaceae) is another large, upper canopy forest tree, and one of the oldest extant native trees of New Zealand (Riley, 2004). It has a fossilized pollen record extending back at least 70 million years, and individual trees can survive for 1,000 years (Riley, 2004). *D. cupressinum* ranges from sea level to 3500 feet in New Zealand, inhabiting forests in lowlands and lower mountain ranges (Richards, 1949).

For germination and growth, *D. cupressinum* requires shade and rich soil with a high mineral content (Richards, 1949; Duncan, 1993). Sites with relatively dry, well-draining soil are preferred. A strong competitor, *D. cupressinum* frequently replaces other upper canopy forest trees when their relationship is not mediated by disturbance events such as floods (Duncan, 1993).

D. cupressinum has long been used by humans. Māori used the gum and bark medicinally, the wood to create canoes, sacred combs and long spears for warfare, and the gum to make pigment for tattooing (Riley, 2004; Clarke, 2007). Captain Cook used the leaves to make spruce beer as an antidote for scurvy (Richards, 1949). More recently, *D. cupressinum* has been an important tree in the New Zealand forestry industry (Dawson and Lucas, 2000), although its use has been restricted by its subsequent decline (Riley, 2004).

C.4 *Daphnia carinata*

Daphnia carinata (Daphniidae) is a freshwater zooplankton which is abundant in many shallow New Zealand lakes. It is often restricted by the presence of predatory fish, with a low biomass in ecosystems with high numbers of fish (Jeppesen *et al.*, 2000; Vakkilainen *et al.*, 2004). *D. carinata* abundance is also influenced by environmental conditions, particularly salinity. In controlled experiments using specimens from Lake Waihola (Otago), Schallenberg *et al.* (2003) found that 50% *D. carinata* specimens would be expected to die after 96 hours in 2.5 psu at 10°C. Salinity also mediates the abundance and diversity of zooplankton communities (Schallenberg *et al.*, 2003). Therefore salinity affects *D. carinata* directly through morbidity and indirectly through controlling the abundance of its predators and competitors. This species appears to be very adaptable however, with different maximum salinities recorded in different lakes around the world (Schallenberg *et al.*, 2003). In Lake Waihola, Otago, *D. carinata* was most abundant at salinities < 0.4 psu, with very low abundances recorded above this level (Schallenberg *et al.*, 2003). This indicates that *D. carinata* may also be very intolerant of high salinities in Waituna Lagoon.

D. carinata enhances water quality by feeding on phytoplankton, though their rate of feeding decreases with increased phytoplankton biomass (Burns and Schallenberg, 2001), suggesting that they become less effective in eutrophic systems.

Ehippia may be produced in spring and autumn as part of a bi-annual cycle of reproduction (Mellors, 1975). They are produced when ecological conditions are becoming less favourable to *Daphnia*, as a mechanism for recolonisation after possible localized extinction, or colonization of new habitats (Pietrzak and Slusarczyk, 2006). Ehippia are bivalved chitinous shells which protect two resting eggs (Mellors, 1975; Pietrzak and Slusarczyk, 2006). The ehippia are pigmented and hardened to protect the eggs after they have been released into the water column (Mellors, 1975). Eggs undergo diapause while within the ehippia (Pietrzak and Slusarczyk, 2006). During this time the ehippia “can withstand freezing and desiccation”, enabling the species to survive unfavourable conditions (Mellors, 1975). *Daphnia pulex* eggs in ehippia were shown to successfully hatch after being passed through fish and laboratory rats (Mellors, 1975), helping *Daphnia* avoid predation (Mellors, 1975). *Daphnia* ehippia may form egg banks in the sediment, enabling recolonisation by delaying diapause and hatching (Pietrzak and Slusarczyk, 2006). Under the appropriate conditions ehippia can remain viable for over one hundred years (Cáceres, 1998).

C.5 *Leptospermum scoparium* (mānuka)

Leptospermum scoparium (Myrtaceae) is a keystone species in many New Zealand ecosystems (Derraik, 2008) and may be the most abundant woody plant in New Zealand (Richards, 1948; Derraik, 2008). The present distribution of *L. scoparium* extends from Stewart Island to Cape Reinga and includes ecosystems from sea level to 1600 m elevation (Derraik, 2008). One of the few species native to New Zealand which became more abundant after human settlement, its range expanded as a result of anthropogenic fire (Cockayne, 1928; Bellingham, 1956). These fires removed approximately two thirds of New Zealand’s forest cover (Cockayne, 1928), creating large areas of habitat for *L. scoparium* (Derraik, 2008).

L. scoparium has a broadly defined niche which includes harsh environments with salt sprays, long-term flooding and wind exposure (Derraik, 2008). It can be found growing in soils which are infertile, acidic, high in nickel and chromium and dry or water-logged (Dawson and Lucas, 2000; Derraik, 2008). Richards (1949) states that “there is nowhere that it cannot grow from bog to dry heath, from sand dunes to mountain tops”.

The growth form of *L. scoparium* depends upon its habitat (Thompson, 1989). In lowlands it forms a small tree, and in mountains it takes the form of a prostrate mat or shrub (Richards, 1949). It prefers open sites where it may form dense thickets. These thickets provide a nursery for forest seedlings, and may in time be succeeded by forest (Richards, 1949; Ogden and Stewart, 1995). For this reason it can be considered a keystone species in the succession of New Zealand forests following disturbance (Ogden and Stewart, 1995; Derraik, 2008).

L. scoparium was an important resource for Māori, as emphasised by its traditional designation as child of the forest God Tāne (Riley, 2004). It was used to treat a wide range of illnesses (Riley, 2004; Derraik, 2008) and for timber (Patel, 1994; Riley, 2004). In Te Reo Māori, “mānuka” means “weapon wood”.

Early European settlers named *L. scoparium* “tea tree” as the leaves were used to make a spicy tea (Riley, 2004). It continued to be used for medicinal purposes and timber, but for many years farmers treated it as a highly undesirable weed and eliminated it by any means possible (Richards, 1949; Derraik, 2008). Health products and honey derived from *L. scoparium* are highly prized and marketed locally and internationally (Derraik, 2008).

C.6 *Myriophyllum triphyllum* (water milfoil)

Myriophyllum triphyllum (Haloragaceae) is a native New Zealand freshwater macrophyte which inhabits deep and shallow lakes throughout New Zealand, including Waituna Lagoon (Orchard, 1979; Robertson and Stevens, 2009). Within New Zealand its geographic distribution includes the North, South, Stewart, Auckland, Campbell and Macquarie Islands and encompasses lakes and rivers from sea level to sub-alpine regions (Orchard, 1979). There is some evidence it is being competitively excluded by introduced species (Kelly and Hawes, 2005) such as *Lagarosiphon major*, *Elodea* and *Nitella* species (Ratray *et al.*, 1991; Suren, 2009).

M. triphyllum is relatively tall for a native New Zealand macrophyte, commonly attaining heights of 1 – 2 m (Ratray *et al.*, 1991; Kelly and Hawes, 2005). A submerged, rooted macrophyte, *M. triphyllum* is most common in deep areas of lakes and rivers, though it can also be found in shallow waters (Orchard, 1979; Robertson and Stevens, 2009). It has three

distinct growth forms which are determined by environmental conditions, primarily water depth (Orchard, 1979).

Although mainly a freshwater species, *M. triphyllum* also tolerates brackish conditions (Orchard, 1979). It prefers relatively slow water velocities, surviving to $4.0 \text{ m}\cdot\text{s}^{-1}$ (Lacoul and Freedman, 2006), and preferentially grows in sediments with a high sand content (Ratray *et al.*, 1991; Lacoul and Freedman, 2006). *M. triphyllum* has been classified as a competitive-ruderal species, signifying its low disturbance tolerance and relatively high competitive ability (Riis and Biggs, 2001). It uptakes nutrients from both the sediment and the water column, and has inhibited root and shoot growth under conditions of eutrophication (Ratray *et al.*, 1991; Hussner *et al.*, 2008).

C.7 *Pinus radiata* (Monterey pine)

Pinus radiata (Pinaceae) is an exotic species which grows better in New Zealand than in its native California (Poole, 2009) and has become a naturalised part of the New Zealand environment. It can grow in coastal environments and tolerates heavy frost, enabling it to also inhabit mountain ranges (Bell, 2001). *P. radiata* thrives in environments with well-drained soil regardless of the nutrient and sand content, and requires full sun (Bell, 2001).

P. radiata was introduced to New Zealand from California in the early 1840s (Bell, 2001; Poole, 2009). It is likely that it was initially grown in pots, before the discovery that *P. radiata* is an ideal tree for shelter belts (Poole, 2009). An *r*-type species which is relatively easy to manage, it became more widespread throughout the country and between 1925 and 1935 was extensively planted (Poole, 2009). This helped stimulate the forestry industry (Clout and Gaze, 1984).

By 2003 only ca. 24% of New Zealand's land mass was covered by native forest (Brockerhoff, 2003); and by 2006, 7% (1.8 million hectares) was covered by exotic forest (Dick *et al.*, 2006). Approximately 90% of the exotic forests are *P. radiata* plantations (Dick *et al.*, 2006), colloquially referred to in New Zealand as "plantation pine" (pers. obs.). Its prominence in the New Zealand landscape and the homogeneity of its stands has resulted in biodiversity concerns (Clout and Gaze, 1984; Brockerhoff, 2003). *P. radiata* is grown for timber and paper pulp and has been highly successful as it is well adapted to the temperate New Zealand climate and has a short rotation of ca. 25 - 30 years (Dick *et al.*, 2006).

C.8 *Pteridium esculentum* (bracken fern)

Pteridium esculentum (Dennstaedtiaceae; formerly known as *Pteridium aquilinum* var. *esculentum*; Brownsey and Smith-Dodsworth, 1989) is a species of fern which is functionally similar to a shrub (McGlone *et al.*, 2005). Native to New Zealand, *P. esculentum* is also found in Australia and many of the Pacific Islands. It commonly occurs in open environments from sea level to sub-alpine regions in New Zealand (Brownsey and Smith-Dodsworth, 1989), where its range is limited by “cool annual temperatures, frost, wind, and shallow, poorly drained and acidic soils” (McGlone *et al.*, 2005).

P. esculentum thrives in full sunlight, and commonly invades disturbed habitats such as farmland and gaps in forest canopies (Brownsey and Smith-Dodsworth, 1989). In these environments the highly flammable dead fronds which accumulate make it very fire prone, maintaining its presence by delaying forest regeneration (McGlone *et al.*, 2005).

Before human arrival in New Zealand, *P. esculentum* was present at a low abundance (McGlone *et al.*, 2005). Māori deforestation transformed the majority of lowland areas in New Zealand and enabled colonisation and expansion by *P. esculentum* (McGlone *et al.*, 2005). *P. esculentum* was a major vegetable component of the diet of early Māori in Southland (Critchfield, 1954; Leach, 1984; Clarke, 2007). Although cultivated by Māori, *P. esculentum* was considered a weed by European settlers. This paradigm continues, particularly in pastoral landscapes, and the low biological diversity of its communities poses a conservation concern in New Zealand (McGlone *et al.*, 2005).

C.9 *Ruppia megacarpa* (large-fruit tassel) and *R. polycarpa* (horse’s mane weed)

Ruppia megacarpa and *Ruppia polycarpa* (Ruppiaceae) are rooted aquatic angiosperms which are native to New Zealand (Brock, 1982). *R. megacarpa* is endemic to Asia and Oceania, and *R. polycarpa* to Oceania (Ito *et al.*, 2010). Both species are distributed throughout New Zealand including Waituna Lagoon, where they are the dominant macrophyte species and integral for maintaining the water quality (Robertson and Stevens, 2009).

Although taxonomically distinct, there are many similarities between *R. megacarpa* and *R. polycarpa*. For this reason they are discussed together below under the collective term

"*Ruppia*", which here excludes other members of the genera. Other *Ruppia* species such as *R. tuberosa* exhibit very different characteristics (Brock, 1982). Where the characteristics of *R. megacarpa* and *R. polycarpa* are distinct from one another they are discussed under their species names.

R. megacarpa is a large, hardy perennial species which grows in aquatic systems with permanent water, such as lakes (Brock, 1982, 1983). It rarely adopts an ephemeral habit (Brock and Lane, 1983). Its breeding method is polycarpic or iteroparous, whereby individuals may breed multiple times, with fewer propagules produced in each event (Brock, 1983). Unlike *R. polycarpa* it does not produce turions, instead relying upon an annual production of seeds (Brock, 1983). *R. megacarpa* seeds establish a permanent seedbank, lying dormant in the sediment until a decrease in salinity initiates germination (Brock, 1983).

R. polycarpa is a small, weak annual species which grows in ephemeral habitats and may complete its lifecycle in as little as six weeks (Brock, 1982, 1983). In suitable environments it may be permanent rather than ephemeral (Brock, 1982). *R. polycarpa* has a monocarpic or semelparous reproductive strategy, whereby individuals reproduce in a single event which results in many propagules (Brock, 1983). *R. polycarpa* reproduces through the production of large quantities of turions (asexual) and seeds (sexual); both of which are functionally similar and hardy, with the ability to survive dry conditions for years (Brock, 1983). The turions are more efficient than seeds, with the ability to germinate multiple times and more rapid growth after germination (Vollebergh and Congdon, 1986).

Ruppia inflorescences are lifted to the surface of the water for fertilisation, and after release *Ruppia* pollen floats on the water surface (Arber, 1920; West, 2004). As fertilisation does not occur underwater *Ruppia* is not a true seagrass (West, 2004). This adaptation for fertilisation on the water surface also means that *Ruppia* plants may be depth limited. Riddin and Adams (2008) found a strong correlation between water depth and the abundance of *R. megacarpa*, with a two month lag between changes in depth and abundance.

Ruppia species are euryhaline, tolerating a wide range of salinities (West, 2004). They usually inhabit brackish waters, but also establish populations in freshwater environments

(Arber, 1920). *R. megacarpa* has a recorded salinity tolerance of 5 - 46 ‰ TDS⁴, and *R. polycarpa* 2 - 66 ‰ TDS (Brock, 1982). These *Ruppia* species infrequently flower at salinities above 50 ‰ TDS, at which salinities plant growth is suspended for a period of senescence (Brock, 1982).

Both species exhibit a reduction in germination with increasing salinity (Short and Neckles, 1999), and Brock (1983) experimentally demonstrated that *R. megacarpa* germination is initiated by a decrease in salinity. Further, *R. polycarpa* seeds increase in size with decreasing salinity (Brock, 1982). In systems which are not intermittently open and closed to the sea a reduction in salinity to facilitate germination may be achieved by disturbance events such as flooding or heavy rainfall (Brock, 1982).

In experimental germination trials with *R. megacarpa* salinity was particularly important when there was no sediment available, with no seeds germinating except in freshwater (Brock, 1982). In contrast, *R. polycarpa* seeds germinate most successfully in freshwater, but turions are equally successful in water with a salinity of 35.5‰ TDS (equal to approximately 100% seawater; Vollebergh and Congdon, 1986). Some turions also germinated at a salinity of 81.5‰ TDS (approximately 225% seawater) though a salinity of 158‰ TDS was inhibitory (Vollebergh and Congdon, 1986). Both seeds and turions of *R. polycarpa* are not affected by prolonged soaking in saline water and shoot and root growth is enhanced by low salinities (Vollebergh and Congdon, 1986).

Even under optimal conditions such as a body of permanent water, *R. megacarpa* and *R. polycarpa* rarely co-exist due to differences in depth requirements. *R. polycarpa* inhabits areas from a 0 - 0.5 m depth, and *R. megacarpa* from 0.5 - 3 m (Brock, 1982; Stevens and Robertson, 2007). Some studies suggest that *Ruppia megacarpa* has a low light requirement (West, 2004), which may be part of the reason for the inter-species differences in habitat depth. *R. megacarpa* also preferentially grows in sediments with a coarse grain size (West, 2004), and both species are slow to react to altered water conductivity (West, 2004).

Ruppia megacarpa is susceptible to disturbance events, but where it is not eliminated it has been found capable of recovery within 2 - 5 years (West, 2004). Plants may be killed by extensive exposure due to a reduction in water levels (West, 2004). *Ruppia* conservation is

⁴ ‰ TDS = parts per thousand total dissolved solvents.

often impeded in such situations by public concern due to unpleasant odours and restricted public access to the waterways (West, 2004).

C.10 *Weinmannia racemosa* (kāmahi, towai)

Weinmannia racemosa (Cunoniaceae) is presently one of the most widespread native New Zealand trees, ranging from sea level to 3000 feet, and from Stewart Island to Thames (Richards, 1949; Dawson and Lucas, 2000). In northern climes it is most commonly found in mountain forests although it is less restricted in Southland (Dawson and Lucas, 2000). A sub-canopy species (Duncan, 1993), *W. racemosa* often germinates on the trunk of a tree fern as an epiphyte before growing into a tree (Dawson and Lucas, 2000).

W. racemosa grows in most environments and soils (Richards, 1949), preferring soils which retain some moisture but are well drained (Bell, 2001). It can tolerate open sites or partial shade (Bell, 2001), but preferentially colonises gaps in forest canopies rather than open sites (Duncan, 1993). Because of its preference for open sites disturbance is important for its maintenance in forest communities (Duncan, 1993) and it is common in regenerating forest (Foster, 2008).

Māori carved handles for stone axes and bird spears from the wood of *W. racemosa*, and used its bark medicinally and to produce dye (Richards, 1949; Clarke, 2007). Honey is made commercially from its nectar (Foster, 2008).

Appendix D. Utility of the methods

The majority of the methods employed in this study were very beneficial, resulting in data which addressed the hypotheses. However the results of some methods were unreliable or not useful. Based upon the present study, a brief discussion of the utility of the methods employed is presented below to aid future research in ICOLLs (intermittently closed and open lakes and lagoons) with humic, peaty sediments.

D.1 X-ray densitometry

X-ray densitometry was used to compare cores prior to extrusion, to determine which cores would be used in this study. Five cores were extracted from Waituna Lagoon, and the three cores with the clearest lithology as revealed on the x-rays were used in this study. The core which formed the basis of this study had a much clearer lithology and far superior length.

This method can also be used to identify material for ^{14}C dating, such as layers of shells (M. Schallenberg, pers. comm., 2009). Further, comparing the x-ray densitometry with the sediment grain size post-extrusion can reveal whether the core was compressed or stretched during extrusion. There was no evidence of either phenomenon in the present study.

Taking x-rays requires specialist equipment and training. In the present study this was contracted to the Dunedin Public Hospital Radiology Department. Interpretation of x-ray densitometry is simple, with darker areas indicating greater density. This method is relatively expensive but requires little time. The cores were x-rayed in segments, with three cores included in each exposure. Results can be seen immediately.

The x-ray densitometry had limited utility in data interpretation, as observed trends were not quantifiable. However this method was important in early stages of the research and is therefore highly recommended. It would be particularly useful if many cores were retrieved, as it enables rapid location of material which may be appropriate for ^{14}C dating. This is particularly beneficial if there are insufficient resources to analyse every core through other methods.

D.2 Organic and water content

The organic and water content was measured to infer changes in the opening regime. The composition of organic material can also be used to establish paleoenvironments (Meyers, 1997), but only the changes in bulk density were important for the present study. The loss on ignition method is relatively simple, requiring only basic laboratory skills such as weighing samples, recording the weights and setting a timer. Specialist equipment and consumables are not required, and the raw data is converted to the percentages of organic material and water using simple mathematical calculations.

Changes in the percentage of organic material were invaluable to the present study, as it enabled reconstruction of the historic opening regime. Changes in the water content were primarily used to compare the two sites. As this method was simple, cost-effective and had a high utility it is highly recommended.

D.3 Sediment grain size

Changes in the sediment grain size were used to reconstruct the historic opening regime. It can also be used to infer changes in the sedimentation rate (Cadmus, 2004), hydrology, vegetation (Yang *et al.*, 2008) and climate (Peng *et al.*, 2005), and is invaluable for explaining changes in other sediment variables such as the retention of pollen. For example, in the present study less pollen was found in sediment composed of ca. 90% sand. This may be due to fast sedimentation while the lagoon was open or a lower retention rate of pollen in coarse grained sediments.

The sediment grain size was measured using the Horiba Laser Scattering Particle Size Distribution Analyser LA-950V2 and a metal sedimentology sieve. This Analyser is a specialized piece of equipment which may be operated successfully with specialized training and generates very detailed grain size distributions. For the present study training took approximately one hour. Samples do not need to be treated prior to analysis, although in some sediment the prior removal of organic material may be desirable; and samples can be tested relatively quickly.

The limitation of this Analyser is that particles over 3 mm diameter cannot be processed. This component of the sediment was extracted and measured using a metal sedimentology

sieve and scales, requiring only basic laboratory skills. This analysis was very labour intensive and must be completed last as there is a high risk of cross-contamination between samples. Unfortunately the data generated in the Analyser presents the percentage of sediment in a range of grain sizes; therefore the coarse gravel (> 3 mm) must be presented separately using a different unit.

Analysis of this proxy is more time consuming in sediments with abundant particles larger than 3 mm diameter. The results were invaluable to the present study, and the use of a grain size analyser presents a relatively easy, accurate and cost effective method of comparing cores from multiple locations. It is highly recommended.

D.4 ^{210}Pb

Analyses of ^{210}Pb concentrations are commonly used to date sediments up to 150 years old (Saulnier-Talbot *et al.*, 2009). In the present study it was used to date the primary core, with a focus on identifying the date of transition to a modified ecosystem. It is standard protocol to have this analysis conducted by specialists, as it requires large amounts of technical training, and chemicals and equipment not available in standard laboratories. Outsourcing this analysis is very expensive, but preferable and often necessary.

MyCore from Chalk River, Canada analysed the ^{210}Pb from Core I and provided an interpretation of the data. Unfortunately this method was unsuccessful due to the small amount of ^{210}Pb in the sediment. This caused complications in the interpretation of the results. As sediment chronologies based on ^{210}Pb data are so useful this analysis is highly recommended. However, alternate methods for inferring dates such as pollen analyses should also be completed. This is particularly important in Waituna Lagoon and other freshwater bodies in Southland, New Zealand which may have very low levels of ^{210}Pb .

D.5 Geotek Multi-Sensor Core Logger

The Geotek Multi-Sensor Core Logger is a highly specialized piece of equipment which is not available in the standard laboratory. It cannot be used without specialist training and/or expert assistance. Fortunately a Geotek Multi-Sensor Core Logger was available at

the University of Otago, and the author could assist with the analysis with a relatively small amount of training.

The Analyser did not take long to read the samples, with the entire analysis completed in less than a week of laboratory time. Additional time should be budgeted for the laborious task of setting up the equipment for the cores, as different core diameters and analyses require different settings. This must be repeated after the cores are opened, and can only be done by a specialist. Further, the Analyser may initially have difficulty reading the samples, and resolving software errors or finding the optimal settings can be very time consuming.

The Geotek Multi-Sensor Core Logger was used to create a high resolution digital image of each core, and to measure electrical resistivity, gamma-ray attenuation, magnetic susceptibility and average reflectance. The most useful output in the context of the present study was the digital image of the cores, as it was a high resolution image which included the entire core. This was beneficial as creating an image of the core using a standard camera would involve the bias of camera angles and potential error when stitching the images together. The gamma-ray attenuation had limited use as it was a back-up method for sediment grain size analyses. The data for electrical resistivity was rejected as it was the opposite of expected trends based upon the sand content, organic material content and known changes after European influence on Waituna Lagoon. The magnetic susceptibility and average reflectance data were not used as they were not useful in the context of this study.

There was no reason to believe that errors in the electrical resistivity data were influenced by the researchers, as the analyses were conducted under the careful guidance of an expert technician. Though very useful when analysing very long cores with ancient sediments, this study suggests that the Geotek-Multi Sensor Core Logger may not be useful in studies on relatively modern humic sediments. Therefore it is not recommended for studies on late Holocene changes in ICOLLs. The superior quality image generated was beneficial but did not justify the time and expense to use this Analyser.

D.6 Charcoal

Charcoal was analysed as an indicator of fire disturbance, to complement the pollen analysis. As both pollen and charcoal can be carried a long distance on wind currents before

deposition in a freshwater environment (Rose, 2004) the combination of both proxies was used to indicate local disturbance events. Initial charcoal analysis attempted to differentiate between micro- and macro-charcoal, as macro-charcoal is more likely to have been deposited near the source (Rose, 2004), however this could not be done quantitatively without error so a basic charcoal count was completed instead.

The analysis of charcoal was simple, requiring only basic laboratory skills and equipment. Bleaching the sediment and extracting the charcoal was a relatively fast and easy procedure, but quantifying the charcoal density took much longer as every charcoal fragment in each sample had to be counted. As an indicator of the time required, the present study analysed seventeen samples for charcoal; in which 216 mg of sediment was counted for charcoal post-bleaching, with 15,768 charcoal fragments counted. Overall this analysis is inexpensive yet very time consuming. Despite the laborious nature and of this analysis it is highly recommended when analysing fire disturbance.

D.7 Pollen

Pollen was analysed to infer changes in vegetation, land use and disturbance regimes (Faegri, 1975), with a focus upon identifying the onset of anthropogenic impact in Waituna Lagoon and catchment. Terrestrial vegetation was used to date the sediments when Pb-210 analyses were unsuccessful, and aquatic vegetation enabled the modeling of *Ruppia* abundance over time.

The process of extracting pollen from the sediment was extremely laborious, requiring large amounts of time, a high level of technical skill and a wide range of laboratory equipment. Large amounts of a range of chemicals were also consumed in the process. The entire process took approximately one week. Fortunately the extraction was successful and the method did not need to be repeated.

Identifying and counting pollen is extremely time consuming and requires a high degree of taxonomical knowledge. Restricting the identification to indicator species as was done in this study greatly decreases the required time and level of expertise. It was fortunate that the pollen of all taxa identified in this study had distinct morphologies, increasing the accuracy of counting.

This analysis is highly recommended in studies where the vegetation is of interest. Although it was extremely time consuming, taking approximately one month for completion, the results had a high utility and enabled an inferential distinction between pre- and post-European sediments. It is further recommended that indicator species are used in preference to identifying every species, as despite the identification of relatively few taxa the process of counting and identification took several weeks. Samples with little pollen were particularly laborious. As an indicator of the time required, seventeen samples were analysed with a total of 5,211 pollen grains identified and 48,883 grains counted. The majority of pollen from non-indicator species was non-descript and reliable identification would be very challenging.

D.8 Foraminifera

Foraminifera were extracted as an indicator of the opening regime. This focused upon the deep sandy sediment from 130 – 100 cm depth as it was advised that foraminifera should be more abundant there. The process of extracting foraminifera was inexpensive and required only basic laboratory skills and equipment. However it was extremely time consuming and it took over one month to complete this analysis for thirty samples.

As this proxy took so long to complete it was not possible to repeat it throughout the core. Further, only five foraminifera were extracted in total from 600 g of sediment. Due to the large amount of processing during extraction it is not recommended to use less sediment per sample when completing this analysis, but using more sediment is not practicable unless this data is a major focus of the study. Further, it was later discovered that the larger, brackish water foraminifer *Ammonia beccarii* could be extracted through wet sieving the sediment. Due to its weight this foraminifer was not extracted using this floating method.

In ICOLLS such as Waituna Lagoon where foraminifera extraction is desirable, it is recommended that the sediment is sieved for macrofossils in preference to this lengthy procedure. The macrofossil analysis will reveal the presence and abundance of *Ammonia beccarii*. This species is ecologically informative and abundant in New Zealand (Hayward and Hollis, 1994). Due to its heavier weight the likelihood that it was blown into the ICOLL from the sea during storms is diminished, making it more informative about the lagoon

itself. If further details of foraminifera including the presence and abundance of smaller calcareous and agglutinated species is required this exhaustive method is recommended; however due to the low numbers of foraminifera extracted it was not useful for the present study.

D.9 Macrofossils

The main objective of analysing macrofossils was the extraction of *Ruppia* seeds to help answer the hypotheses about its abundance under a natural opening regime. Smaller macrofossils were extracted from the shorter Core III (Eastern arm) because they were discovered when sieving one of the samples. The extraction and counting of these taxa required only basic laboratory skills and equipment, and did not cost any money. The identification was much more complicated and time consuming, particularly as there was not a published guide on the seeds of New Zealand monocotyledons.

The utility of this method was limited as few *Ruppia* seeds were found, and smaller macrofossils were only extracted from Core III, which had an unknown sedimentation rate and chronology. Some useful data was generated, particularly the changing abundance of the freshwater zooplankton *Daphnia ephippia*, and the brackish water foraminifera *Ammonia beccarii*. The data was not as useful as other proxies such as the organic and sand content, sediment grain size and pollen, but is recommended in studies where such macrofauna could provide valuable information. This method would have been more useful in the present study if it were completed at both sites, but unfortunately it was not part of the research design, with macrofossils discovered near the end of the laboratory analyses.