Environment Waikato Technical Report 2004/25

Rehabilitation of Lake Waikare : Experimental Investigations of the Potential Benefits of Water Level Drawdown

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Executive Summary

Lake Waikare is a large shallow lake that currently forms part of a flood-control scheme operated by Environment Waikato, and includes a weir at the lake outlet to facilitate water level control. The lake historically contained healthy aquatic plant populations, but is now characterised by high turbidities and low light penetration, which make it incapable of supporting submerged vegetation. Lake drawdown has been used successfully overseas to restore the light climate and submerged vegetation in shallow lakes. Drawdown can enhance rehabilitation by consolidating sediment and making it less prone to wave resuspension, by increasing light penetration to the sediment surface allowing plant growth, and by directly reducing wind-wave action and assisting coarse fish control via a smaller surface area and volume. Environment Waikato recognises that the weir provides an opportunity to artificially control the lake level to enhance its health, and that one option is a water level drawdown over the spring and summer months. Therefore, Environment Waikato contracted NIWA to assess the potential effectiveness of water level drawdown for lake rehabilitation.

Lakebed sediment was transferred to concrete troughs where it was drained and exposed for periods of up to 6 months over summer. Changes in the physical and chemical properties of the sediment were monitored and compared with an undrained control trough. The troughs were rewetted following exposure and the resistance of sediment to resuspension was measured. In addition, dried sediment from the bed of Lake Waikare was submerged and cultured for 6 months to assess the likely seed germination response to drawdown and refilling of the lake.

Water level drawdown in Lake Waikare doesn't appear to hold significant benefits for improving the light climate through altering sediment properties. There was some consolidation of surficial sediments, but light-attenuating sediments were still resuspended and high turbidities were measured following inundation of desiccated sediments.

Establishment of aquatic vegetation to stabilise sediments and take up nutrients is crucial to rehabilitation of Lake Waikare. To do this requires a suitable light climate for aquatic plant growth. This study has shown that lake drawdown has the potential to initiate rehabilitation by creating a suitable light climate for plant growth at the sediment surface. The experiments showed that lakebed sediment is well suited to both terrestrial and aquatic plant growth. It appears that marginal/wetland and terrestrial plants are particularly likely to colonise the exposed sediment surface during drawdown, but the seedbank for aquatic plants is limited.

Although drawdown provides an opportunity to initiate plant growth in the lakebed sediments, the fate of this vegetation upon refilling the lake remains uncertain. The establishment, survival and persistence of submerged vegetation once the lake is returned to its stable level is uncertain due to the following factors:

- The aquatic plant seedbank and its germination response to drying and rewetting appears to be limited.
- Terrestrial and many marginal/wetland plants are unlikely to survive long underwater.
- Pest fish such as Koi carp are a threat to submerged vegetation. The exact relationship between coarse fish and vegetation in the lake is unknown, but other examples such as Hamilton Lake suggest coarse fish are detrimental to the establishment of aquatic plants. Assuming they are detrimental, then some consideration into methods of removal or control of pest fish is advisable before attempting rehabilitation.

- The lake is hyper-eutrophic, so algal growth and associated light climate reduction may occur following any initial improvement in light climate (Reeves et al. 2002).
- The lake forms part of a flood control scheme and during floods the vegetation will be stressed by reductions in the light climate caused by water level increase, particularly where this involves turbid inflows (Reeves et al. 2002).
- Growing vegetation will be subjected to wave disturbance on refilling the lake, and wave-induced entrainment of light-attenuating sediment will occur unless a dense coverage of aquatic vegetation has been established.

Our conclusion based on the present study and that of Reeves et al. (2002) is that lake drawdown does not provide the sole answer for the rehabilitation of Lake Waikare. The study has demonstrated that drawdown does hold some benefits for the lake, and could form part of the rehabilitation process. But it is our opinion that the number and scale of the problems the lake suffers (e.g. koi carp, large wind-wave fetch, hyper-eutrophic) make it a poor candidate for rehabilitation.

1 Introduction

Lake Waikare once supported a mix of aquatic native plants in appreciably clearer waters than occur now. Visual clarity in the lake decreased by the 1940's, coincident with land clearance, and complete collapse of submerged vegetation occurred in 1977/78 (Reeves et al. 2002).

Macrophyte communities reduce sediment resuspension by consolidating sediments and dampening wave activity, and are an integral part of the lake ecosystem, providing habitat for fish and invertebrate communities. Shallow lakes that have lost macrophyte communities usually exhibit frequent periods of resuspension, high turbidity and low light penetration (e.g. James et al. 2002), conditions that are all typical of Lake Waikare today (Reeves et al. 2002).

If macrophyte communities are to be re-established in Lake Waikare, then the penetration of photosynthetically active radiation into the water (referred to from hereon as the "light climate") must be improved, so they can survive long enough to reach heights sufficient to reach the water surface. Therefore, rehabilitation of Lake Waikare depends fundamentally on restoring the light climate of the lake. Reeves et al. (2002) estimated the median depth limit of submerged plant growth due to light climate to be about 0.4 m in Lake Waikare. Reeves et al. (2002) demonstrated that light penetration was linearly related to turbidity in Lake Waikare, i.e. light climate would improve if turbidity were reduced. Furthermore, they showed that turbidity was linearly related to suspended sediment concentration in Lake Waikare with a 1:1 ratio, i.e. reducing suspended sediment concentrations would reduce turbidity and improve the light climate (see glossary for definition of, and relationships between, visual clarity, light penetration and turbidity). Fine-grained inorganic sediments presently dominate the high turbidity and light attenuation in the lake, with notable increases in turbidity observed when waves are actively stirring the lakebed. In Lake Waikare there is an abundance of clay-sized sediment that is easily resuspended and maintained in suspension so that the lake is always turbid even after prolonged periods of calm weather (Reeves et al. 2002, Stephens 2003).

Reeves et al. (2002) identified the following mechanisms for improving the light climate of the lake through reducing suspended sediment concentrations:

- Reduction of suspended sediment inputs from the catchment or shoreline erosion through riparian management (already actioned), or by wetland filtering.
- Improve sheltering of sediments through wave barriers – high effectiveness but only in protected areas.
- Increase flushing of the lake by the Te Onetea Stream – thought to have low effectiveness due to large hydraulic residence time of the lake.
- Mussel bio-filtration – thought to have low effectiveness due to low mussel density.
- Consolidate lake sediments by drawing down lake levels – thought to have medium to high risk with unknown effectiveness.

Additional mechanisms for lake rehabilitation could be:

- Aggregation of suspended sediments by application of a flocculent (e.g. alum treatment).
- Removal of pest fish to lessen bioturbation and promote filtering animals (e.g. Meijer and Hosper 1997).
- Increase lake level fluctuations to aid the establishment of marginal wetland species.

This purpose of this study was to assess the previously unknown effectiveness of lake water level drawdown for lake rehabilitation. Lake level drawdown has potential benefits that are relevant to several of the restorative mechanisms listed above. Overseas, lake drawdown has been successfully used to enhance sediment properties and rehabilitate macrophyte communities in shallow lakes (e.g. de Groot & van Wijck 1993; Helsel & Zagar 2003). The drawdown and associated desiccation causes dewatering and consolidation of lakebed sediment, making it less prone to wave resuspension by aggregating the excessive abundance of very fine material. During drawdown the lake surface area and volume are dramatically reduced, so pest fish can be more easily targeted and destroyed (James et al. 2002). Lake Waikare has an existing outlet weir that could be used to draw lake levels down.

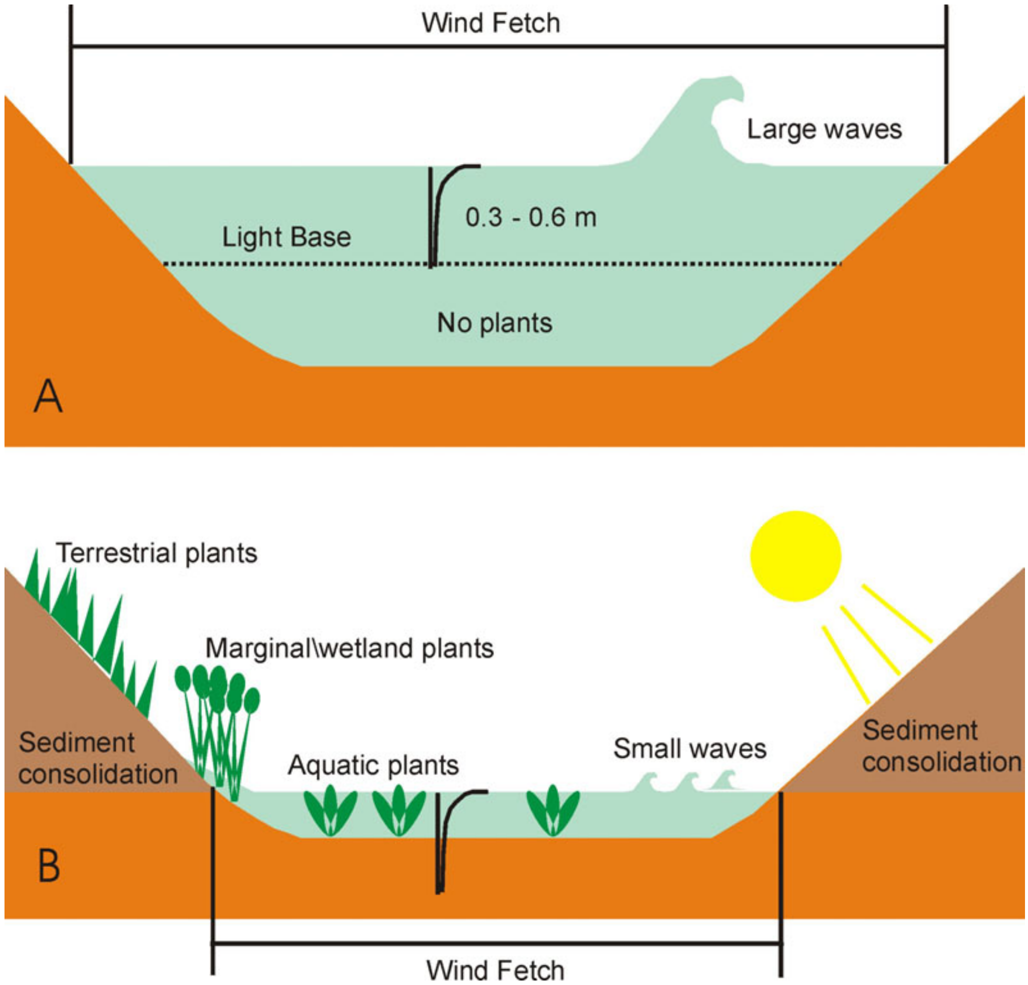

Figure 1: **Schematic of Lake Waikare: A) as it exists now and B) the potential benefits of lake drawdown including sediment consolidation, reduction of wave stress through reduced wind fetch, and bringing the sediment surface into the light penetration zone to allow plants to grow.**

Therefore, the potential benefits of water level drawdown in Lake Waikare are (e.g. Figure 1):

1. Improve the light climate by consolidating and aggregating fine sediments through the process of desiccation (drying), effectively making them a) more resistant to resuspension following rewetting and/or b) altering the light-attenuating properties by changing the dominant grain size in the sediment through flocculation/aggregation.
2. Drawdown also offers an additional restorative mechanism, the ability to short-circuit the feedback link between water clarity and plant growth by allowing plants to establish in a subaerial environment, or in shallow water within the light base.

Drawdown exposes the sediment to photosynthetically active radiation and allows plants to grow, including terrestrial plants. Plant growth is likely to assist in binding sediments and increase wave dampening following rewetting. The successful recolonisation of plants would depend on sources of plant inocula being available to repopulate the lake and their ability to germinate in the desiccated and rewetted sediment.

3. Facilitate pest fish removal over a reduced lake area.
4. Reduce wind-waves by reducing wind fetch (temporary benefit).

Lake Waikare currently forms part of a flood-control scheme operated by Environment Waikato that includes a weir at the lake outlet to facilitate water level control. Environment Waikato recognises that alongside its flood-control role, the weir provides an opportunity to artificially control the lake level to enhance its health. Therefore, Environment Waikato contracted NIWA to assess the effectiveness of lake water level drawdown for lake rehabilitation. The weir could potentially be used to reduce the surface area of Lake Waikare to about ¼ of its present surface area through a level reduction of about 1.3 m (Grant Barnes, *pers comm.*). Because the lake is part of a flood-control scheme, with most floods in winter, and also an important game-bird habitat (with shooting season beginning in May), the practical time constraint for drawdown would be about 6-months during spring and summer. This study investigates the first 2 of the potential benefits listed above, using two experimental designs.

In the first set of experiments, lakebed sediment was desiccated in concrete troughs for different lengths of time. The impacts of desiccation upon sediment consolidation, aggregation and resuspension following rewetting were investigated. Plant growth trials were also conducted in the troughs to assess the ability of lakebed sediments to sustain vegetation.

In a second experiment a seed bank investigation provides complementary information on the expected extent of plant colonisation upon drawdown and refilling of the lake. The approach used was to measure the germination response from cores of sediment, following drying to mimic lake drawdown. This sampling focused on sheltered, shallow water sites, where drawdown and refilling was most likely to produce conditions amenable to seed germination and plant establishment. Here we provide an indication of the extent, and composition of recruitment from the lake seed bank.

2 Methods

2.1 Trough desiccation and rewetting experiments

2.1.1 Sediment collection

Sediment was collected from the nearshore area of Lake Waikare (Figure 2) on 12th September 2003 using a drain suction vehicle (Figure 3). This entailed sucking surface sediment from the shallow margins of the lake (approximately 15–20 m from the shore) down to a depth of approximately 20 cm. As large volumes of lake water were also sucked into the tanker during this process, this had to be decanted 4 times during the collection process. The decanting process could have impacted on the study by changing the grain size distribution of the sediment, because we would expect more slow-settling fine sediment to have been lost during the decanting process than fast-settling coarse sediment. Although we expect that this did happen to some degree, grain size analyses shown later indicate that decanting effects were minor, and as discussed later, it can be ignored in the context of the resuspension experiment results.

The sediment was transported to the Ruakura Research Centre, Hamilton, and distributed into 6 experimental troughs (4 for sediment resuspension trials, and 2 for aquatic macrophyte trials). Each trough comprised a 60 cm high circular concrete farm-trough, filled with sediment to a depth of 15–20 cm (Figure 4).

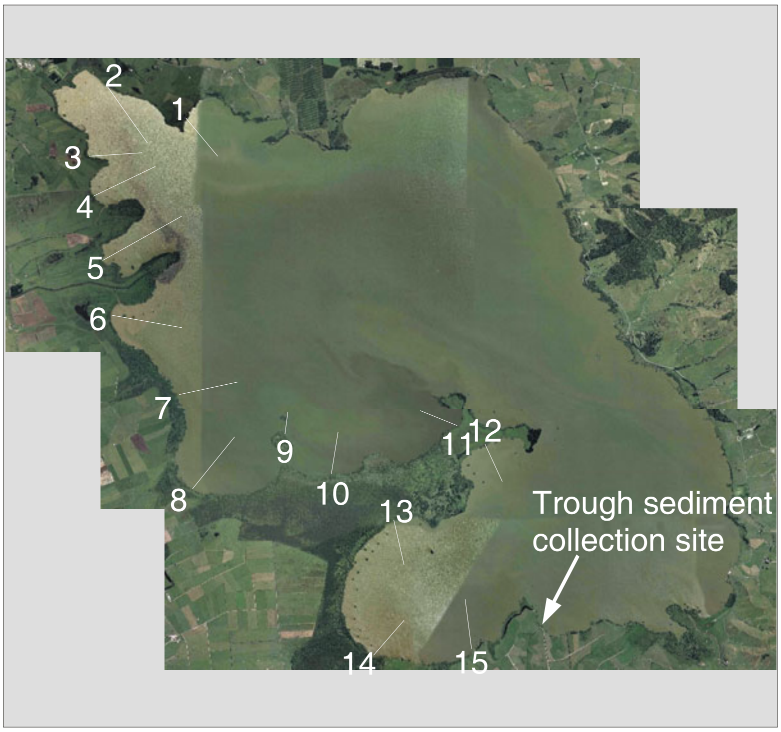

Figure 2: **Aerial photo overlay of Lake Waikare, showing the trough-sediment collection site and locations of 15 seed bank sample sites.**

Figure 3: **Drain suction vehicle used to collect ~6 m^3 of lakebed sediment.**

Figure 4: **Discharging sediment slurry into concrete troughs, 23 September 2003.**

2.1.2 Trough treatment

Four troughs were used in the sediment desiccation-resuspension experiments and the remaining two troughs were planted with macrophytes to test whether macrophytes could recolonise the desiccated sediments. The two macrophyte troughs were included in the final resuspension experiment, but were otherwise treated separately.

Turf plants were collected from Lake Waikare (Site 6, Figure 2) on November 12, 2003. These plants comprised a total cover on damp banks and shallow water beneath a willow margin. Species included *Glossostigma sp.*, *Lilaeopsis novae-zelandiae*, *Myriophyllum sp.*, *Pratia angulata* and *Hydrocotyle novae-zeelandiae*. Small clumps (c. 30-40 mm diameter) of plants and sediment were planted on December 19th, 2003, in 2 troughs containing dried and re-wetted sediment, with the planted area comprising approximately 3-5 % of the tank area.

Of the 4 sediment desiccation-resuspension trial troughs, one control trough was immediately filled with water (Hamilton City tap water treated to remove residual chlorine). The remaining three dry troughs were exposed to prevailing weather conditions for 2, 4 and 6 months respectively, before being filled with water (a drainage hole prevented the troughs filling naturally with rainwater). The climate at Ruakura is similar to that at Lake Waikare, so sediment exposure is likely to have been similar. The maximum exposure time of 6 months was chosen to comply with a maximum drawdown period of 6 months during the spring-summer period, since the lake would need to be full for the game-bird hunting season in May-June, and is likely to be inundated during winter floods. The 2 and 4 month exposures were chosen to test for systematic changes with time, but also to see if considerable benefits could be gained from shorter sediment exposure times, which may fit with a more regularly fluctuating water level regime.

Table 1 shows the trough treatment schedule and Figure 5 illustrates the exposure times for the 6 troughs. Sediment was redistributed between troughs about 2 weeks after the sediment was first gathered because the drain suction vehicle was unable to access all troughs during unloading. The upper 10 cm of sediment in all troughs was then thoroughly stirred and mixed with the overlying water with the aim of getting a natural settling distribution at the sediment surface, i.e. fines at the sediment surface as found in the lake. The aim was to counteract the possible loss of fines from the decanting process during sediment collection, by ensuring the surface sediment layer on which tests were to be undertaken had a natural grain size distribution.

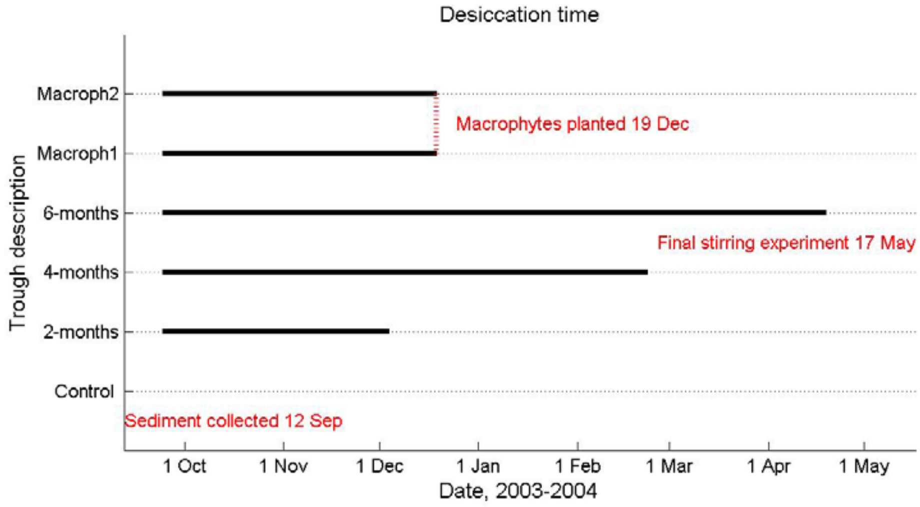

Figure 5: Trough sediment exposure periods; desiccation (drying) indicated by heavy lines.

Table 1: Trough treatment schedule, 2003–2004. Days are specified relative to the redistribution and activation of trough sediments.

Day	Date	Activity
-12	12-Sep	Collect sediment.
0	24-Sep	Sediment redistributed amongst 6 troughs and all filled with water.
21	15-Oct	All troughs except control drained and control trough covered with black polythene to exclude light (algae and plants).
71	4-Dec	Rewet 2-months-dry.
86	19-Dec	Macrophytes planted in 2 troughs following rewetting.
152	23-Feb	Rewet 4-months-dry.
208	19-Apr	Rewet 6-months-dry.
236	17-May	Final resuspension experiment on all troughs.

2.1.3 Experimental tests

Bulk density is the mass of dry soil, including solid particles, water and air, contained in a unit volume. A soil or sediment containing heavy particles such as clay minerals will generally have a higher bulk density than one made up of light particles such as organic matter. Porous sediment will have a lower bulk density than a tightly packed sediment (Head 1992). Bulk density was calculated by averaging 3 samples from each trough. 50 ml volumetric samples were collected using a syringe and bulk density calculated following weighing.

Moisture content is the mass of water that can be removed from a measured mass of soil by heating at 105°C (Head 1992). Following bulk density tests, moisture content was determined by pre and post weighing after drying for 3 days.

The mass lost from a soil on ignition is related to the organic content of soils containing little or no clay (Head 1992). Clay sediment is not really suitable for loss on ignition tests unless organic content exceeds 10%, because material other than organic matter can contribute mass loss on ignition (Head 1992). Following bulk density and moisture content tests, loss on ignition was calculated by weighing the sediment before and after ignition of dry soil at 400ºC for 8 hrs. However, loss on ignition results were erratic due to high clay content and are not reported.

Three weeks after rewetting, resuspension experiments were performed on the exposed desiccation-resuspension troughs, and again on all troughs on 17 May 2004 (Table 1). Bed sediment was resuspended by creating a rotating current in the troughs using a hand-operated rotating paddle (Figure 6). Current speeds were held steady for 5 minutes and then ramped up to a higher speed increment (e.g. Figure 7) until it became obvious that massive resuspension was occurring, or until it was difficult to increase current speeds further. Current speeds were measured just outside the paddle radius with a PVM-2A flow velocity meter (Montedoro Whitney Inc, San Luis Obispo, Ca). Samples were taken at the end of each 5-minute stirring speed increment for analysis of suspended sediment concentration and particle size distribution.

Figure 6: 2-months-dry trough with stirrer paddle in place, before (left) and during (right) stirring, 23 Feb 2004 (Table 1).

Turbidity was also measured at the end of each 5-minute stirring speed increment for comparison with suspended solids concentration, since turbidity provides an index of lake optics. Turbidity was measured using an Analite 155 Nephelometer (BWD Precision Instruments Pty, Ltd, Melbourne Australia).

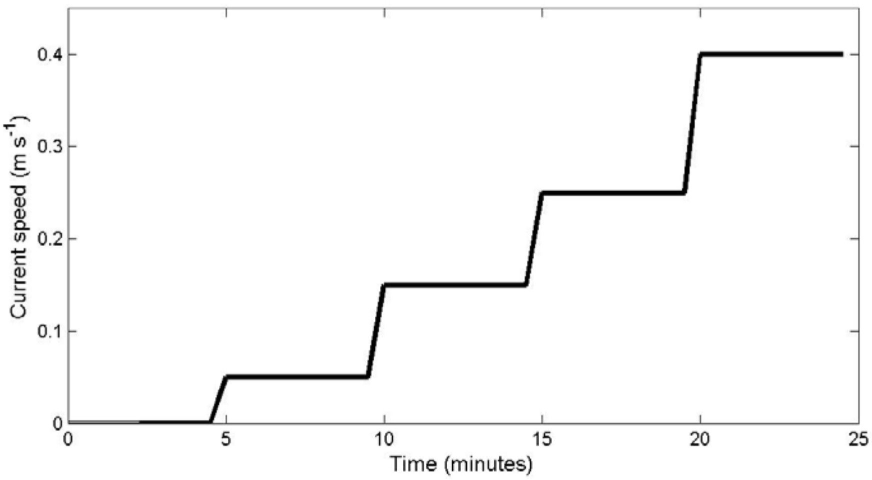

Figure 7: Example of current speed regime applied during sediment resuspension experiments.

The stirring method had two drawbacks:

1. It was difficult to reproduce exactly the same speeds in all the stirring experiments. The approach taken was to increase speeds until sediment resuspension was observed to begin (a process easily seen in the clear trough water at low speeds), and thereafter to increase speeds by 0.05 m s^{-1}.

2. Stirring speeds were increased slowly to allow momentum to be transferred into the troughs with minimal turbulence, but it can be seen from the right-hand photo in Figure 6 that some turbulence around the paddles was unavoidable. Therefore, reported velocities are averages with typical turbulent variations of ± 0.02 m s^{-1}. The accelerating and decelerating flows associated with turbulent eddies will cause sediment to be entrained more easily than during laminar flow, just as occurs due to accelerating flows under waves (Nielsen 1992). Minor turbulence in the troughs is probably more representative of actual resuspending forces in the lake than laminar flow, but it does reduce the precision of the experimental results.

Sediment and water quality tests were undertaken to assess potential nutrient release. A single mid-column water sample was collected 1 day and 3 weeks after rewetting desiccated troughs (Table 1), and the control trough sampled simultaneously. These were analysed for total phosphorus (TP), dissolved reactive phosphorus (DRP), total nitrogen (TN), ammoniacal nitrogen (NH_4-N), and nitrate nitrogen (NO_3-N).

2.2 Seedbank methods

Intact cores of sediment were collected at 15 sites (Figure 2, Appendix 2) along the western shoreline on November 11 and 12, 2003. Four cores (100 mm deep, 85 mm diameter) were collected from each of three water depths per site, ‘shallow’ (0.3-0.6 m depth), ‘mid-depth’ (0.9-1.1 m depth) and ‘deep’ (1.3 m depth), providing a total of 176 samples. Sample depths were selected in reference to the average lake depth of c. 1.3 m (Reeves et al. 2002), to include sediments that were most likely to be exposed during drawdown. Cores were inserted into the sediment to full depth, capped top and bottom and retrieved (Figure 8).

Figure 8: An intact core from 1.3 m depth is being checked before storage.

The top cap of the cores was removed and cores were dried under a clear, rainproof canopy at ambient temperature (Figure 9). After 35 days the cores were rewetted by overhead sprinkler, and cultured under conditions considered favourable for submerged seed germination; at 1.0 m water depth in an outdoor tank receiving ambient light reduced to ~15%, under shade cloth.

Figure 9: Dried sediment cores showing a range of sediment types sampled.

After 3 months (23 March 2004) and 6 months (15 June 2004) seedling emergence was detected by eye, plants were counted and identified as far as possible.

3 Results

3.1 Trough desiccation and rewetting experiments

3.1.1 Photographic essay

The following series of photographs provide a visual comparison between troughs and treatments.

Figure 10 shows the 4- and 6-months-dry troughs on 23 February 2004. The 4-months-dry trough was partially colonised by invasive terrestrial weeds, and exposed surficial sediment is seen to have formed tension cracks upon drying. The 6-months-dry trough was completely colonised by invasive terrestrial weeds. Figure 11–Figure 13 show all troughs on the day of the final resuspension experiment.

The cracking of the exposed sediment in the 4-months dry trough (Figure 10) indicates that desiccation of surficial sediment has occurred. The terrestrial (Figure 10) and aquatic (Figure 13) vegetation growth shows that there is no impediment to plant growth in Lake Waikare sediments if a suitable seedbank is present. The aquatic plants were hand-planted, but the terrestrial plants are wind born weeds from surrounding farmland, whose root systems may help stabilise sediment for some time post-rewetting. Similar terrestrial plant colonisation could be expected at Lake Waikare upon drawdown.

Figure 10: 4-months-dry (left) and 6-months-dry (right), 23 February 2004.

Figure 11: Control (left) and 2-months-dry (right), 17 May 2004. The 2-month-dry trough has the stirrer in place, just before beginning the resuspension experiment.

Figure 12: 4-months-dry (left) and 6-months-dry (right), 17 May 2004. Invasive terrestrial vegetation has been carefully trimmed before resuspension experiments.

Figure 13: Macrophyte 1 (left) and 2 (right), 17 May 2004. The original planted area comprised approximately 3-5 % of the tank area on 19 Dec 2003. By June 2004, >90% of the sediment surface was colonised by *Glossostigma* sp. in both troughs.

3.1.2 Sediment physical properties

A sediment sample from the collection site had a median volume-based grainsize of 103 μm (very fine sand, e.g. Lewis & McConchie 1994) and a numbers-based median size of 1 μm (clay), (Figure 14). Clay-sized particles made up nearly 40% of the sample by number, and this increased to 70% with ultrasonic dispersion of aggregates, showing that many of the larger particles were aggregated clays. Sediments in the control trough had lower numbers of clay particles than found in the lakebed sample, possibly due to flocculation upon settling in the still trough environment. However, when sediment aggregates were broken into their constituent particle sizes using ultrasonic dispersion, the grain sizes of both lakebed and trough sediment were nearly identical (compare Figure 16 and Figure 17). This shows that either the decanting of water during collection had not removed a disproportionate number of clay particles, or that the method of sediment placement within the troughs had allowed the surface sediments to settle in a natural order. The grain size distribution near the surface of the trough sediments was therefore representative of the lakebed sediments.

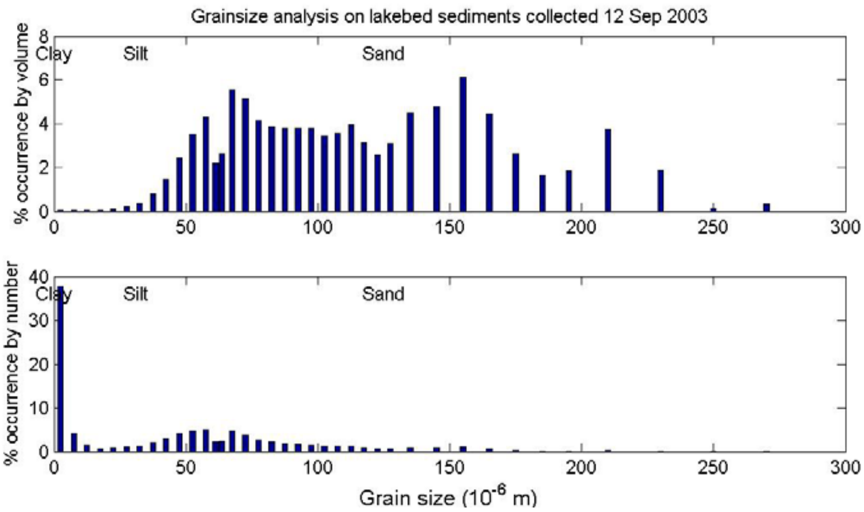

Figure 14: Grainsize distribution plots of lakebed sediment at the collection site, sampled immediately before collection.

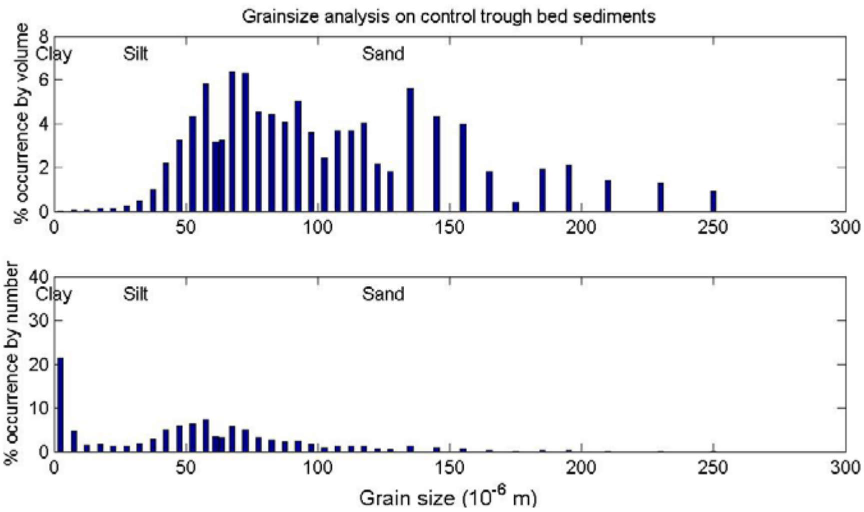

Figure 15: Grainsize distribution plots of surficial control trough sediment, sampled on 17 May 2004.

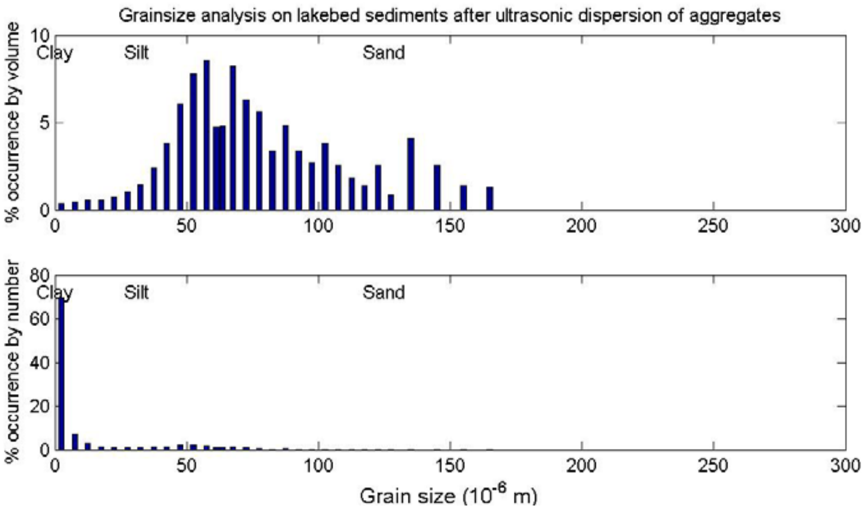

Figure 16: Grainsize distribution plots of lakebed sediment at the collection site, after ultrasonic dispersion of aggregates.

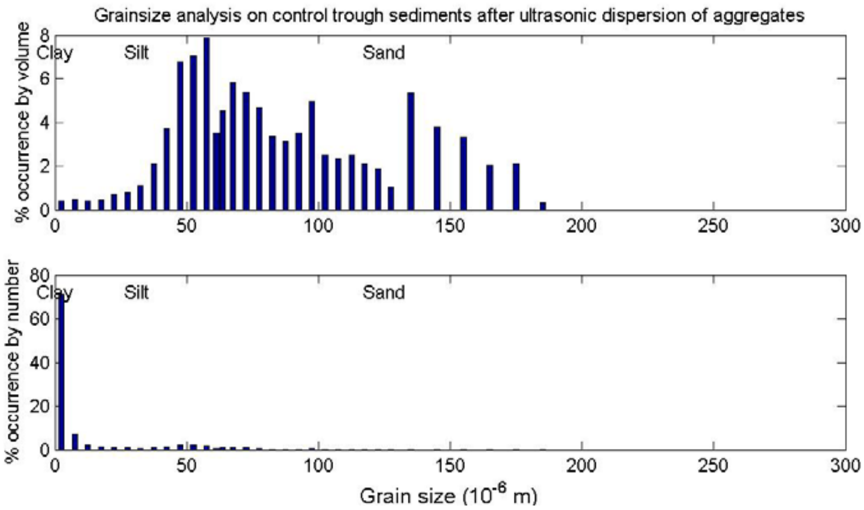

Figure 17: Grainsize distribution plots of surficial control trough sediment, after ultrasonic dispersion of aggregates.

Bulk density values were consistent throughout the trial, ranging between 1.42 and 1.63 g ml^{-1}. The results show little consolidation of individual troughs, and little relative change between troughs (Figure 18).

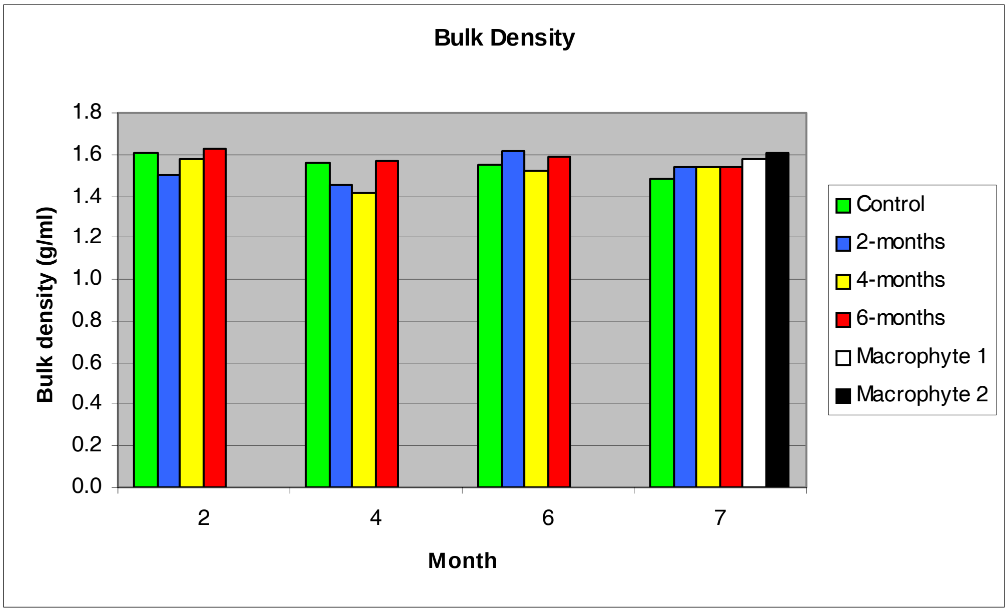

Figure 18: Bulk density of trough sediment.

Moisture contents showed some variation throughout the trial, ranging from 26 to 43% (Figure 19), but the control trough showed variation of more than 7%, suggesting some natural variation within the sample, or imprecision in the method of determination. Within this range of variation, the moisture contents were relatively consistent, and moisture contents were similar in the final sampling regardless of treatment.

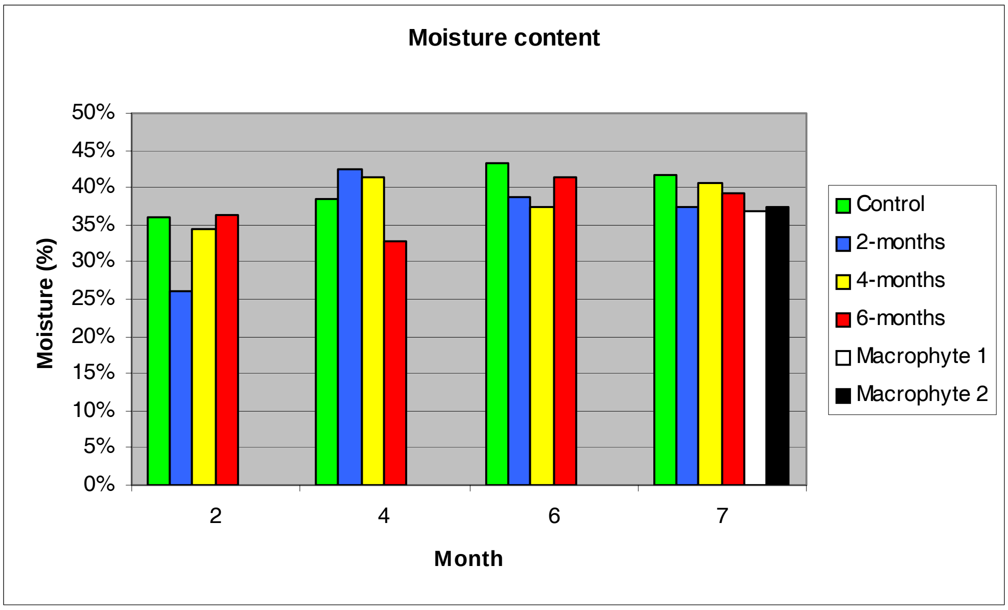

Figure 19: Moisture content of trough sediment.

Loss on ignition values were low, suggesting organic matter contents of 5% or less and generally under 2%. Chemical analyses of percent carbon averaged 0.9% with a maximum of 1.6%, which is consistent with the typical organic matter carbon content of about 50%.

3.1.3 Sediment resuspension and turbidity

Figure 20 shows resuspended sediments versus current speed during the resuspension experiments, while Figure 21 shows turbidity versus current speed. Table 3 presents the data. An aquatic plant (*Callitriche* sp.) with long fibrous strands was present in the "macrophyte 2" trough. This plant became caught in the stirrer and disturbed the sediment, compromising the resuspension results for this trough, which are not presented

Resuspension was negligible in all troughs at speeds ≤ 0.05 m s^{-1} and only the control trough showed increased resuspension at speeds below 0.1 m s^{-1}. Resuspension began to increase abruptly at speeds of about 0.15 m s^{-1} (Figure 20), suggesting that the critical erosion threshold of the sediments had been exceeded. These visually observed erosion threshold speeds are shown in Table 2.

Table 2: Critical erosion threshold speeds during resuspension experiments. These are the current speeds at which sediment grains were visually observed to begin lifting off the sediment surface and into the water column.

Trough description	Critical erosion threshold (3-weeks after rewetting)	Critical erosion threshold (17 May 2004)
Control	0.07 m s^{-1}	-
2-months-dry	0.15 m s^{-1}	< 0.1 m s^{-1}
4-months-dry	0.15 m s^{-1}	< 0.1 m s^{-1}
6-months-dry	0.25 m s^{-1}	-
Macrophyte 1	-	0.25 m s^{-1}

Drying reduced resuspension in the 4-months- and 6-months-dry troughs at all speeds, and the initial resuspension rate was lower in the 2-months dry trough relative to the control (Figure 20, zoomed view).

The dried and vegetated troughs (4-months, 6-months, macrophyte troughs, e.g. Section 3.1.1) plotted with lower slopes than other troughs, i.e. sediment resuspension rates were lower for these troughs.

The increase of turbidity with current speed had similar trends to suspended sediment concentration (Figure 21), turbidities remained comparatively low in the vegetated troughs compared with the unvegetated troughs.

The second resuspension of the 4-months-dry trough (4-months (2)) showed that the sediments had returned to an easily resuspended state. The first resuspension experiment in the 4-months-dry trough showed considerable “improvement” over the 2-months dry trough, with lower resuspension rates and turbidity. But after being inundated for 2 months and then re-stirred, the 4-months dry trough exhibited resuspension and turbidities with a similar current-response to the unvegetated 2-months-dry trough, indicating that the benefits of desiccation had been lost (the terrestrial plants in the 4-months-dry trough were still surviving well underwater in the clear light climate). This probably occurred because sediments resuspended during the first stirring did not reconsolidate, but may also indicate a gradually lowering of erosion thresholds with time spent inundated. It demonstrates that although drying the sediments can raise the critical erosion shear stress, this rise is only temporary, and once a sufficiently strong stirring event has occurred the sediment may revert to an easily erodable state.

For most treatments, volatile (organic) suspended sediment concentrations formed high proportions (mostly > 50%) of the total suspended sediment concentrations at the start of resuspension tests (Table 3), and probably consisted of algae or floating plant matter in the water column. But although there was some additional resuspension of organic material during the resuspension experiments, percent organic matter generally dropped to less than 15%, showing that it was mostly the inorganic sediments being resuspended (The exception being macrophyte 2, discussed above).

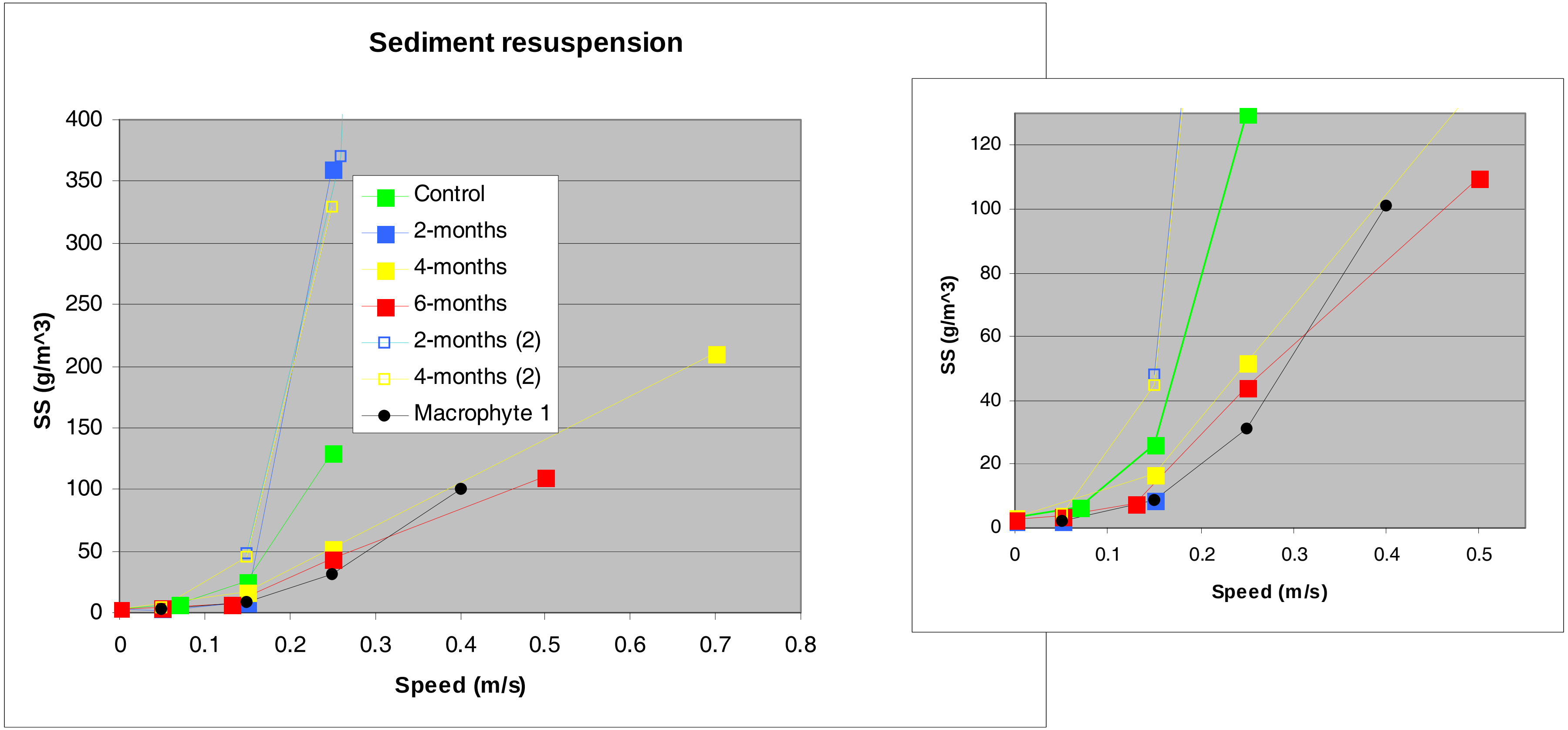

Figure 20: Suspended sediment concentration versus current speed during sediment resuspension experiments, including zoomed view. Stirring of the 2-months, 4-months and 6-months dry sediment troughs were conducted 3-weeks after rewetting. Stirring of the control, 2-months (2), 4-months (2) and the two macrophyte troughs was conducted 3-weeks after rewetting the 6-month dry sediments, thus 2-months (2) was re-stirred after 5.5 months of rewetting, and 4-months (2) was re-stirred after 2.8 months of rewetting.

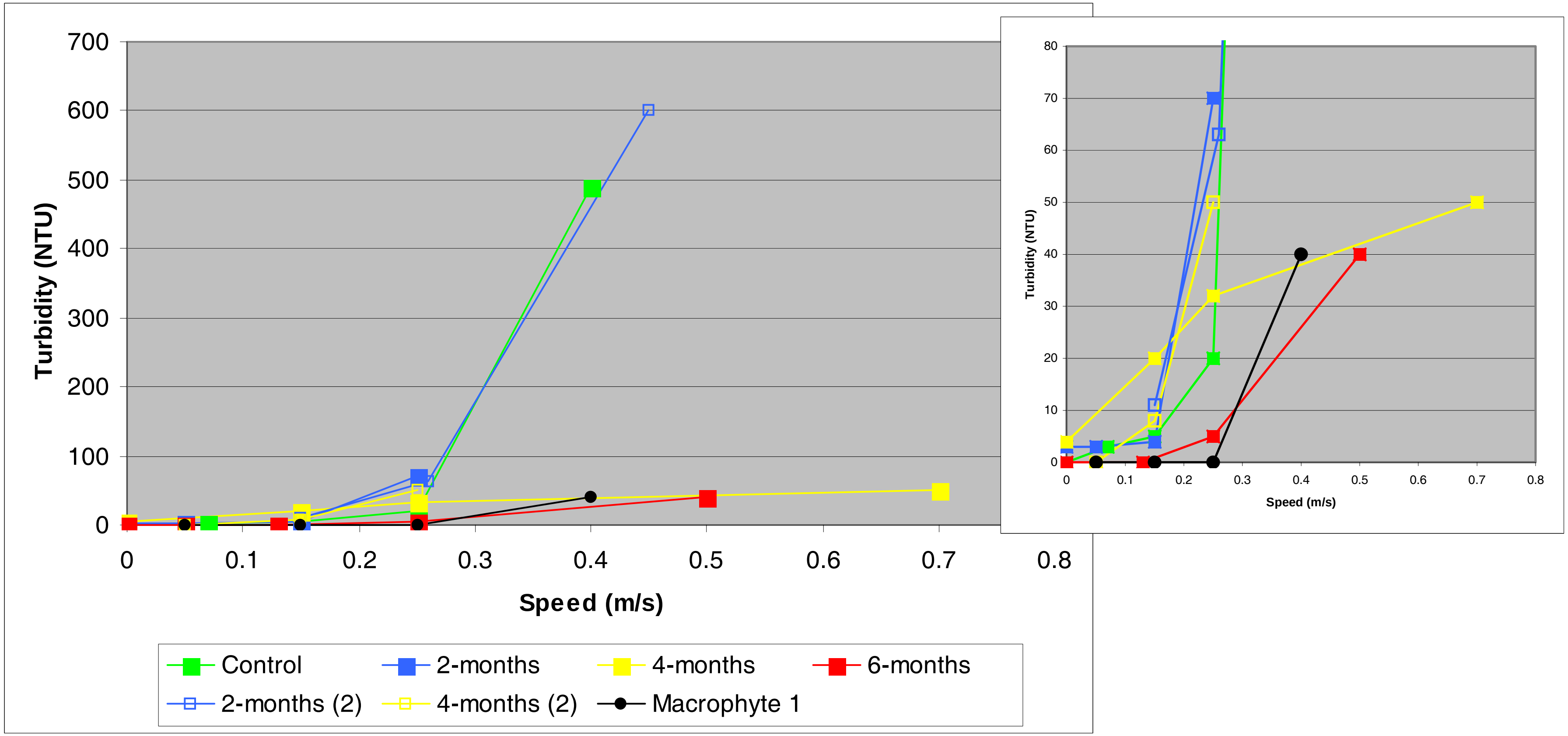

Figure 21: Turbidity versus current speed during sediment resuspension experiments, including zoomed view. Stirring of the 2-months, 4-months and 6-months dry sediment troughs were conducted 3-weeks after rewetting. Stirring of the control, 2-months (2), 4-months (2) and the two macrophyte troughs was conducted 3-weeks after rewetting the 6-month dry sediments, thus 2-months (2) was re-stirred after 5.5 months of rewetting, and 4-months (2) was re-stirred after 2.8 months of rewetting.

Table 3: Sediment resuspension experiment results. SS = suspended sediment concentration, VSS = volatile (organic) suspended sediment concentration Vol-Med = volume-based median grainsize, #-Med = numbers-based median grainsize.

Treatment	Date	Speed ($m\ s^{-1}$)	SS ($g\ m^{-3}$)	VSS ($g\ m^{-3}$)	Turbidity (NTU)	Vol-Med (µm)	#-Med (µm)
Control	17-May	0	3.1	1.8	0		
		0.07	6.7	2.6	3		
		0.15	26	2.9	5	90.7	1.2
		0.25	130	7.4	20	73.6	1.1
		0.4			490		
2-months	22-Dec	0	2.4		3		
		0.05	2.1		3		
		0.15	8.7		4		
		0.25	360		70		
4-months	12-Mar	0	3.4	1.0	4		
		0.05			6		
		0.15	17	5.6	20		
		0.25	52	7.4	32		
		0.7	210	22	50		
6-months	17-May	0	3.0	2.0	0		
		0.05	3.6	3.4	0		
		0.13	7.4	3.6	0		
		0.25	44	9.8	5		
		0.5	110	16	40	125.9	0.9
Macrophyte 1	18-May	0.05	2.3	2.0	0		
		0.15	8.9	4.2	0		
		0.25	31.1	7.8	0		
		0.4	101	13.8	40	87.7	1.3
Macrophyte 2	18-May	0.1	69.4	49.2	10		
		0.2	110	75.8	60		
		0.5	279	121	100		
2-months (2)	17-May	0.15	48	3.4	11	79.8	1.1
		0.26	370	19	63		
		0.45	4100	200	600	87.8	1.2
4-months (2)	17-May	0.05	4.4	2.0	0		
		0.15	45	5.0	8		
		0.25	330	26	50	103.3	1.1

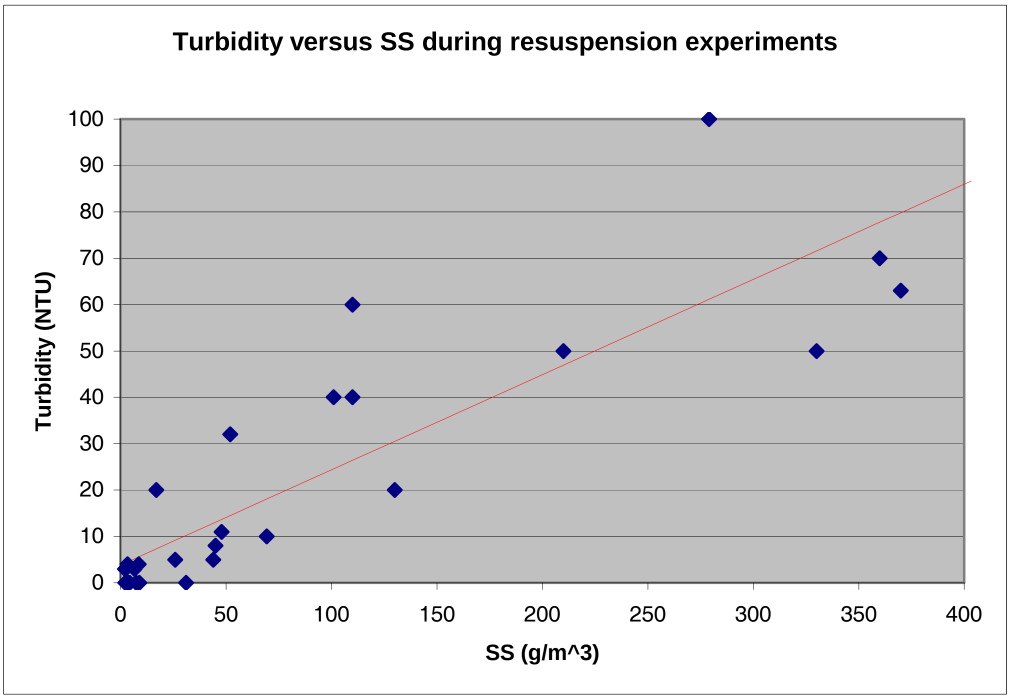

Figure 22: Turbidity versus suspended sediment concentration for all sediment resuspension data. The linear fit is described by *turbidity* = $0.21 \times SS + 3.81$, with $r^2 = 0.76$. The two highest outliers have been omitted (4100 g m^{-3}:600 NTU, unknown g m^{-3}:490 NTU).

Table 3 shows suspended sediment median grainsize statistics, from water samples collected during resuspension tests, and Figure 23 shows a grainsize distribution plot for the control trough suspended sediments. The analyses indicate that some aggregation of particles occurred on drying the sediment, but this did not greatly alter the grainsize distributions. Median grainsizes by particle volume were classified as fine sand for all suspended sediment samples, but a high proportion of clay-sized particles were also found during resuspension, irrespective of trough treatment, and median grainsizes by particle number were classified as clay. Both the volume- and numbers-based grainsize distributions were similar between the lakebed sediment (Figure 14, Figure 16), the control trough bed sediment (Figure 15, Figure 17) and water-column suspended sediments (Figure 23).

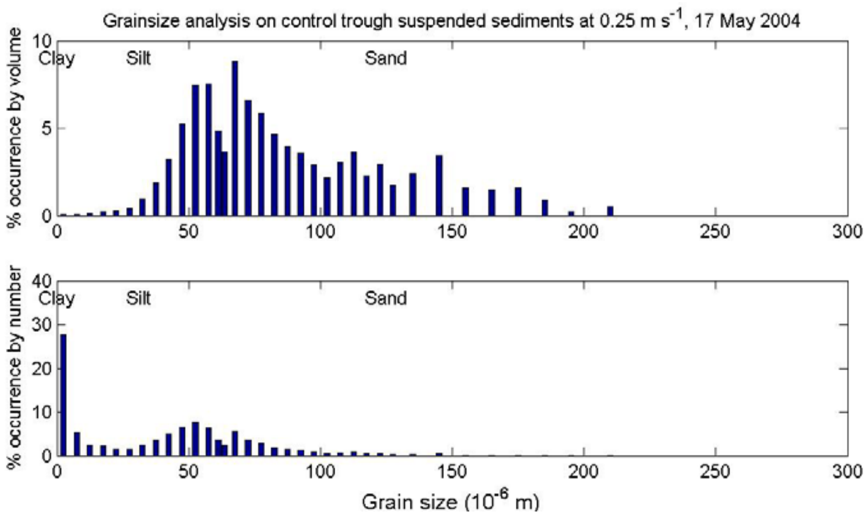

Figure 23: Grainsize distribution plots of suspended sediments collected from the control trough at a stirring speed of 0.25 m s^{-1}.

3.1.4 Sediment and water chemistry

Table 4 presents results of sediment analyses while Table 5 presents results of water column analyses for the troughs. In general, the limited number of samples made nutrient analyses difficult to interpret, but the trends in NH_4-N and NO_3-N concentrations are consistent with release of NH_4-N from sediments, followed by nitrification (oxidation of NH_4-N to NO_3-N by autotrophic bacteria) under aerobic conditions. Subsequent denitrification (NO_3-N $\rightarrow$ N_2O $\rightarrow$ N_2) under anaerobic conditions (such as occurs when fine clay sediments are again waterlogged) may have occurred. Nutrient levels, particularly total nitrogen (TN) and phosphorus (TP) were generally much higher following placement than found in later tests. After an initial drop following placement, TP levels remained similar in the control trough, but TN showed a steady decline, probably due to settling of particulate nutrients out of the water column. Other nutrient variables exhibited little change. Particulate carbon values indicate very low levels of organic matter in the sediment.

The nutrient results show some evidence of nutrient release from sediments following rewetting, but in minor quantities compared to levels occurring naturally in the lake (Background lake TN and TP levels in Lake Waikare water are 1100 and 180 mg m^{-3} respectively (Reeves et al. 2002)). Therefore, any nutrient release from lakebed sediments into the water column following drawdown and rewetting of Lake Waikare is unlikely to be important given the high nutrient levels already found in the lake.

Table 4: Nutrient analysis results for trough sediments. PC = particulate carbon, POC = particulate organic carbon, PN = particulate nitrogen, PP = particulate phosphorus, NH_4-N = ammonium nitrogen, NO_3-N = nitrate nitrogen, TN = total nitrogen (units converted from %), TP = total phosphorus.

Name	ID	Date	PC %	POC %	PN %	PP %	NH_4-N (mg/kg)	NO_3-N (mg/kg)	TN (mg/kg)	TP (mg/kg)
Control	Placement	25-Sep	0.47	0.5	0.05	0.02	24	<1	700	160
	Follow up	5-Dec	0.63	0.64	0.08	0.02	22	<1	700	155
2-months	Placement	25-Sep	0.77	0.6	0.05	0.02	27	<1	800	164
	1-day rewet	5-Dec	0.46	0.41	0.04	0.02	9	2	600	145
4-months	Placement	25-Sep			0.06	0.02	34	<1	900	166
	1-day rewet	25-Feb	1.08	0.77	0.07	0.02	<5	8	800	172
	3-week rewet	12-Mar	1.01	0.84	0.06	0.02	<5	<1	700	160
6-months	Placement	25-Sep	0.96	0.83	0.07	0.02	36	<1	1000	176
	1-day rewet	20-Apr	1.63	1.23	0.09	0.02	<5	<1	900	172

Table 5: Nutrient analysis results for trough water. NH_4-N = ammonium nitrogen, NO_3-N = nitrate nitrogen, TN = total nitrogen, TP = total phosphorus, DRP = dissolved reactive phosphorus.

Name	ID	Date	NH_4-N (mg/m^3)	NO_3-N (mg/m^3)	TN (mg/m^3)	TP (mg/m^3)	DRP (mg/m^3)
Control	Placement	25-Sep	183	94	2940	478	7
	2-months	5-Dec	58	396	1210	34	3
	4-months	25-Feb	34	222	517	15	2
	6-months	20-Apr	25	286	658	40	1
	Round up	17-May	6	2	293	41	1
2-months	Placement	25-Sep	639	60	2530	420	5
	1-day rewet	5-Dec	19	119	309	20	2
4-months	Placement	25-Sep	1280	23	3320	352	3
	1-day rewet	25-Feb	3	272	376	9	3
	3-week rewet	12-Mar	16	31	509	45	1
6-months	Placement	25-Sep	497	70	2680	460	5
	1-day rewet	20-Apr	3	136	277	52	31
	3-week rewet	17-May	4	2	392	35	1

3.2 Seedbank results

Limited seedling emergence (3 cores) was noted after 1 month. After 3 months, a germination response was observed in 16 cores (9% of samples) from 9 sites (Table 6). At the final assessment (6 months), 15 cores from 9 sites recorded a germination response, with most cores (12) in common with the previous assessments. Fourteen of the cores that showed a germination response were collected from shallow water (0.3-0.6 m), one core from medium depth (0.9-1.1) and three cores were collected from 1.3 m depth.

The overall germination response from the collected cores averaged 0.34 plants per m^2. Much of the response was from cores collected from ≤0.6 m depth, with an average of 2.79 plants per m^2

At least 10 plant species were recorded (Table 6), although not all could be definitively identified because they were immature, without inflorescence (e.g. *Juncus* sp.). The most frequently encountered plants were a rush, probably *Juncus articulatus*, and the herb, *Ludwigia palustris*. The swamp lily *Ottelia ovalifolia*, at least two other *Juncus* species and an *Eleocharis* species (probably *E. acuta*) also established. Obligate submerged plants were limited to the charophyte species, *Chara australis* and *Nitella leonhardii*; the latter identified by an oospore (seed) case adhering to the root system. In addition, mosses and the liverwort, *Riccia*, were noted. It was noted that cores collected from 1.3 m water depth especially, became irreversibly altered by drying, showing considerable shrinkage, a firm to hardened surface and cracking (Figure 9, Appendix 3). Due to the low germination response from 'deep' samples we cannot tell if hardened sediments affected plant establishment. This reflects the small volumes of sediment in the cores and the drying conditions used, and may not occur during drawdown.

Table 6: List of the cores that showed a germination response at each assessment (three and six months) and tentative species identifications, together with collection information (site, depth), where species codes are as follows: OO; *Ottelia ovalifolia* (R.Br.) Rich., LP; *Ludwigia palustris* (L.) Elliott, JA *; Juncus ?articulatus* L., JB; *Juncus ?bulbosus* L., JP; *Juncus ?planifolius* R. Br., JX?*; Juncus* sp., EL; *Eleocharis ?acuta* R.Br. CA; *Chara australis* Brown, NL; *Nitella leonhardii* R.D.W.

Site	Depth	Three months				Six months			
		Core 1	Core 2	Core 3	Core 4	Core 1	Core 2	Core 3	Core 4
2	0.4								1 CA
3	0.3		1 JX?	1 JX?			1 JA?	1 JA?	
4	0.3	8 JX?	1 JX? 1 LP	2 JX?	13 JX? 4 LP	2 JA 6 JA?	1 LP	2 JA	5 JA 6 JA? 4 LP
5	0.4				1 JX?				
8	0.4				1 JB 1 JX?				1 JB
9	0.6			1 OO				1 OO	
10	1.3								1 OO
10	0.9-1.1			1 LP				1 moss	
11	0.3	3 JX? 1 LP				1 JA			
12	0.4	4 LP 1 CA 6 JX? 1 OO	6 LP 3 JX?		1 LP 5 CA 1 OO 2 JA?	1 OO 3 LP 1 EL 2 JA? 2 JP 1 CA 1 NL	4 JA 5 LP		3 CA 1 OO 1 LP 1 JP
13	1.3	1 Moss		1 *Riccia*					

4 Discussion

4.1 Sediment physical properties

Barko and Smart (1986) demonstrated experimentally that low sediment density and high organic matter content suppressed macrophyte growth, while higher density sediment with lower organic matter content were associated with greater macrophyte growth. Overseas examples of sediment desiccation experiments (e.g. James et al. 2002; Helsel et al. 2003) have shown marked changes in these sediment properties for the benefits of macrophyte growth.

Big Muskego Lake sediments nearly doubled in density following drawdown and rewetting (from 0.078 to 0.149 g ml^{-1}), while moisture content and particulate organic matter also decreased significantly (from 92% to 86% and from 45% to 39% respectively, Helsel et al. 2003). Likewise, experimental desiccation of Lawrence Lake sediments resulted in substantial sediment consolidation, as the percentage moisture content (80%) and organic matter (12.4%) content declined, while sediment density (0.212 g ml^{-1}) increased after the rewetting process (James et al. 2002).

This did not occur with the Lake Waikare sediment on drying. Bulk density, moisture content and organic matter remained essentially unchanged. Lake Waikare sediments are very different to the above overseas examples, being 7–20 times denser, having about half the moisture content and 5–17 times less organic matter in their natural state. It would appear that organic matter has been broken down and dispersed in Lake Waikare since submerged vegetation populations collapsed in 1978/79, probably aided by the shallowness of the lake that facilitates regular stirring of the lakebed sediments by wind-waves and consequent winnowing or oxidation of organic matter. Without plants as a source of organic matter the lakebed now consists mainly of inorganic silt and clay sized material that forms a considerably denser medium.

Higher density sediments may provide a better plant rooting medium for macrophytes, resulting in increased root contact with sediment particles and associated nutrients (Barko & Smart 1986). The colonisation of the troughs by both terrestrial invasive weeds and by planted macrophytes (Section 3.1.1) shows that the sediments are well suited to plant growth if there is an inoculum and the light climate is suitable.

4.2 Sediment resuspension and turbidity

One of the primary aims of the study was to investigate whether drying would bind sediments, reduce resuspension and improve the light climate on subsequent rewetting.

Crusting of the sediment surface during the drying experiments (Section 3.1.1) indicated a hardening of the sediment surface and critical erosion thresholds increased with drying time, showing an increased resistance to erosion from the desiccation process. Furthermore, desiccation reduced resuspension in the 4- and 6-months-dry troughs and the initial resuspension rate was lower in the 2-months-dry trough relative to the control.

Therefore we expect that lake drawdown would reduce resuspension of lakebed sediments following rewetting by about half, for small erosional forces, regardless of plant presence. This would be particularly relevant to lake sediments presently deeper than about 1 m, that experience a mean wave-orbital velocity of about 0.05 m s^{-1} or less and are less likely to be recolonised by plants because of depth limitations.

However, follow-up resuspension tests of the 2- and 4-months-dry troughs showed resuspension rates to have increased markedly over the initial tests, particularly in the

4-month-dry trough that had higher initial erosion resistance. This probably occurred because sediments resuspended during the first stirring did not reconsolidate. Although drying initially increased resistance to resuspension, these benefits were soon lost with re-inundation. This can be expected to occur following drawdown in Lake Waikare, because even sediments in the deep areas of the lake (at current lake levels) will experience some wave stirring during energetic events (Reeves et al. 2002).

The resuspension experiments showed that suspended sediment concentrations were linearly related to turbidity, as expected. Turbidity is an index of visual clarity, but was also linearly related to light penetration, or light climate in Lake Waikare (Reeves et al. 2002). The turbidity : SS ratio was lower in the trough experiments than the background 1:1 ratio in the lake (Reeves at al. 2002), because there were higher proportions of sand-sized particles (which are largely optically irrelevant) in the trough water column during active stirring. Reeves et al. (2002) also observed a drop in the turbidity : SS ratio during active resuspension events, as more sand particles were resuspended. Despite the lower turbidity : SS ratio found in the troughs, Figure 22 shows that there remained a high proportion of clay-sized particles in resuspension, and these clay particles are highly light attenuating and contribute disproportionately to restricting light penetration (Davies-Colley et al. 1993). Turbidities measured during trough resuspension were similar to those found in the lake, suggesting that despite the initial increased erosion resistance resulting from desiccation, resuspension of light-attenuating particles would still occur in the lake when energetic wave stirring occurred.

There remains some doubt about the resuspending power of currents at the measured trough stirring speeds compared with wave-orbital velocities of the same magnitude in the lake. The acceleration associated with wave-induced currents is known to resuspend sediment at lower mean speeds relative to laminar flow. But the trough-stirrers created turbulent eddies that would have caused sediment to be entrained more easily than during pure laminar flow (e.g. Nielsen 1992). Therefore we guess that the recorded trough current speeds are probably similar to or slightly less effective at resuspending sediment than equivalent wave orbital speeds in the lake. Therefore, the occurrence of resuspension in the troughs is almost certain to be associated with equivalent or higher resuspension in the lake under similar current speeds at the lakebed. Since resuspension occurred following desiccation in the troughs, it can also be expected in the lake following drawdown and rewetting.

Interpretation of the desiccation results are complicated by the growth of terrestrial plants in the 4-months and 6-months-dry troughs (Section 3.1.1). For example, at higher erosion speeds, resuspension in the 2-months-dry trough was similar to the control, whereas the 4- and 6-months-dry troughs maintained a low rate of resuspension. This was probably due to the presence of plants in the latter two troughs, whose resuspension profile as a function of current speed was similar to the planted macrophyte troughs.

Areas that became colonised by plants had increased resistance to resuspension, regardless of whether they were terrestrial invasive weeds or planted macrophytes. Follow-up resuspension tests were not undertaken for the fully vegetated troughs, so we cannot conclusively say that these benefits would have persisted for the 6-months-dry trough. However, the presence of planted macrophytes clearly reduced resuspension, supporting abundant evidence from other studies that aquatic macrophytes reduce sediment resuspension and so maintain water clarity (e.g. Scheffer 1998). This shows that, if plant colonisation of Lake Waikare sediments can be promoted, sediment consolidation and improved water clarity should ensue.

4.3 Algal light attenuation

Algae are not presently nutrient limited in the lake, but light limited. Therefore a “flush” of nutrients from the sediment is unlikely to cause increased algal blooms or deteriorated lake health. Instead, an improvement in lake water clarity may increase the algal biomass, by allowing algae to survive at greater depth. Reeves et al. (2002) estimated a maximum depth of submerged vegetation growth of 1.1 m, based on light attenuation from existing background algal and humic substances in Lake Waikare. Using background TN and TP values of 1100 and 180 mg m^{-3}, a chlorophyll-*a* concentration of 70 $\mu g\ l^{-1}$ is estimated, which corresponds to a 1% light level of 2–3 m due to algae alone (Tilzer, 1987). These estimates are a significant improvement on the median 1% light level (light base) of 0.4 m currently found in the lake (Reeves et al. 2002). The estimates suggest that even in ideal light conditions for algal growth, algal light attenuation would not exclude aquatic plants.

4.4 Seedbank

Overall, there was a low germination response from the sampled seed banks. For example, seed bank samples collected and cultured in the same way but from Lake Rotoroa (Hamilton) recorded an average of 289 plants per m^2 compared to <1 plant per m^2 in Lake Waikare. This low response is likely to reflect a low seed bank density in the sediment of Lake Waikare. This lake has been essentially de-vegetated for c. 30 years, during which time many residual seeds would age, germinate and die-off, or become buried beyond the depth limit for recruitment (e.g. Dugdale et al. 2001). Prior to de-vegetation the lake was dominated for many years by beds of *Egeria densa*, an oxygen weed which does not produce seed, but which excludes seed-producing native plants. Both de-vegetation events and oxygen weed invasion have been shown to impact deleteriously on the seed density and species richness of submerged seed banks (de Winton and Clayton 1996).

A trend for sediments from shallow water to have a greater seed content or germination response has been recognised previously (de Winton and Clayton 1996). In the case of Lake Waikare this is likely to reflect shorter distances from shallow areas to the sources of inocula for marginal/wetland plants (e.g. drains and wetlands) and/or seed sorting by waves to the coarser, shallow sediments.

While most lake seed banks are dominated by obligate submerged plants (e.g. de Winton and Clayton 1996, de Winton et al. 2000), only two charophyte species germinated from Lake Waikare sediments. Earlier, sediment sieved for seed content had detected viable oospores of these charophytes at low densities in samples from Lake Waikare (Reeves et al. 2002).

In contrast, the germination response of Lake Waikare cores was dominated by marginal/wetland species (*Juncus* sp. *Ludwigia palustris*, *Eleocharis* sp.), many of which grow in drains and backwaters around the lake and so provide an inocula source for the lake seed banks. Viable seed may also be introduced via the digestive tract of visiting waterfowl (e.g. *Ottelia*). Amphibious turf plants (e.g. *Glossostigma* sp., *Lilaeopsis novae-zelandiae*) did not germinate and establish, despite the fact that they were observed at the shoreline (e.g. site 6).

The plants that responded in this trial would be those with propagules that tolerate drying and which can germinate underwater. Seeds of many obligate submerged plants are tolerant of drying. For example, germination of charophyte oospores is enhanced by drying of seed bank sediment (de Winton et al. 2004). Marginal/wetland plants are known to be suited to fluctuating water levels and we do not expect seed germination rates to be reduced by drying of seed bank sediment. Germination of marginal/wetland plants may however, be affected by the extent of inundation, with some able to germinate on damp sediment but requiring subsequent growth to keep pace with water level rises. This investigation did not seek to mimic lakebed inundation following drying, due to uncertainties over the extent of drying and regime of re-filling. Consequently, we may have underestimated the establishment marginal/wetland plants that cannot tolerate sustained inundation, as well as establishment by terrestrial plants.

There are likely to be opportunities for marginal/wetland and terrestrial plants to establish during any drawdown of Lake Waikare, such as following rainfall events. These plants may bind sediments as their root systems develop, and provide temporary cohesion for sediments upon lake refilling. While terrestrial plants will be lost, the fate of marginal/wetland plants upon inundation is difficult to predict, as it would depend on subsequent conditions for growth, and levels of disturbance. The marginal/wetland species listed in Table 6, with the possible exception of *Juncus planifolius*, are able to grow to at least 1 m depth in lakes (NIWA macrophyte data).

The majority of responding seedlings had germinated by three months of summer following inundation, suggesting a relatively rapid establishment of plants from available seed is possible during late spring to summer, a period considered most favourable for plant growth. However, their subsequent survival, spread and biomass development would depend upon water depth/light, disturbance and sediment fertility.

5 Conclusions and recommendations

Water level drawdown in Lake Waikare doesn't appear to hold significant benefits for improving the light climate through altering sediment properties. There was some consolidation of surficial sediments, but light-attenuating sediments were still resuspended and high turbidities were measured following desiccation.

Establishment of aquatic vegetation to stabilise sediments and take up nutrients is crucial to rehabilitation of Lake Waikare. To do this requires a suitable light climate for aquatic plant growth. This study has shown that lake drawdown has the potential to initiate rehabilitation by creating suitable light climate for plant growth at the sediment surface. The experiments showed that lakebed sediment is well suited to both terrestrial and aquatic plant growth. It appears that marginal/wetland and terrestrial plants are particularly likely to colonise the exposed sediment surface during drawdown, but the seedbank for aquatic plants is limited.

Although drawdown provides an opportunity to initiate plant growth in the lakebed sediments, the fate of this vegetation upon refilling the lake remains uncertain. The establishment, survival and persistence of submerged vegetation once the lake is returned to its stable level is uncertain due to the following factors:

- The aquatic plant seedbank and its germination response to drying and rewetting appears to be limited.

- Terrestrial and many marginal/wetland plants are unlikely to survive long underwater.

- Pest fish such as Koi carp are a threat to submerged vegetation. The exact relationship between coarse fish and vegetation in the lake is unknown, but other examples such as Hamilton Lake suggest coarse fish are detrimental to the establishment of aquatic plants. Assuming they are detrimental, then some consideration into methods of removal or control of pest fish is advisable before attempting rehabilitation.

- The lake is hyper-eutrophic, so algal growth and associated light climate reduction may occur following any initial improvement in light climate (Reeves et al. 2002).

- The lake forms part of a flood control scheme and during floods the vegetation will be stressed by reductions in the light climate caused by water level increase plus turbid inflows (Reeves et al. 2002).

- Growing vegetation will be subjected to wave disturbance on refilling the lake, and wave-induced entrainment of light-attenuating sediment will occur unless a wide coverage of aquatic vegetation has been established.

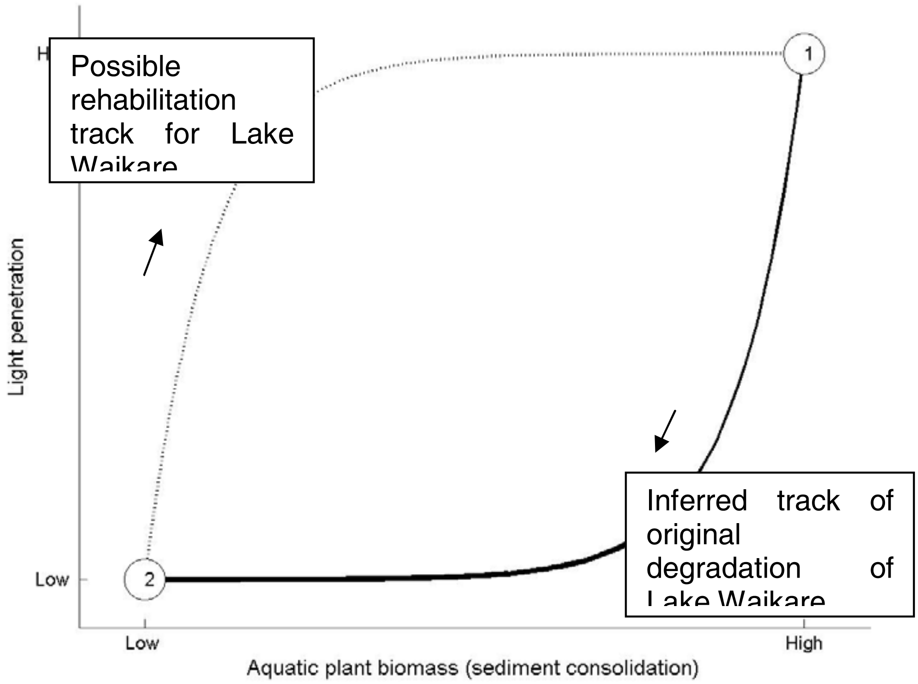

Figure 24: Schematic hysteretic model of Lake Waikare degradation and recovery track.

To re-establish aquatic vegetation requires that conditions (e.g. light climate) be made *better* than required to sustain established vegetation, as illustrated in Figure 24. Decline of light penetration in Lake Waikare probably preceded the loss of (sediment stabilising) aquatic plants. Originally (state 1) the lake was comparatively clear and had high plant biomass (Reeves et al. 2002). Plants would have damped wave action as well as consolidated sediment, preventing erosion and sediment resuspension. The change in lake condition was most plausibly initiated by inflow of very turbid (and light attenuating) water from catchment erosion (Reeves et al. 2002). But, considerable plant matter (photosynthetic tissue) was above the (compressed) euphotic zone, so that plants persisted despite worsening water quality. When macrophytes in the lake finally collapsed (in 1978) the lake “catastrophically” moved (solid curve, Figure 24) to a new state of much lower plant biomass and much poorer light penetration (state 2). To rehabilitate the lake may mean achieving greatly improved light penetration before plants will recolonise and grow sufficiently to consolidate the sediment and move the lake condition along the dotted path to eventually achieve (something like) the original state (1).

To achieve a greatly improved light climate to establish plants would require the following actions to be in place:

- A reduced wave climate – practically achieved by reduction of fetches through lake drawdown. This would need to be maintained until plants established sufficiently to provide their own wave damping action, then water level would need to be gradually raised at a rate that allowed the plant canopy height to adjust (e.g. Figure 25).

- No high water levels or very turbid water that would reduce the light climate – the flood control scheme could not operate during the sensitive period.

- Possible removal or control of pest fish.

- Possible nutrient reduction in the lake and inflowing waters.

The time period required for lake rehabilitation would be dictated by the aquatic plant establishment and elongation rate, which involves complicated feedback between the inocula and unknowns such as the quality of light penetration, and the disturbance by coarse fish and wave action. Reinstatement of water levels following drawdown would need to be linked to field observations and would probably need to occur over a longer period than the 6-months preference (e.g. Figure 25). We would estimate that water levels would need to be reinstated over 1–3 annual cycles to balance wave action and plant establishment/wave-damping. Tall-growing aquatic plants that can reach close to the water surface as levels rise are required. Suitable plants would be Ruppia, Potamogeton's and Myriophyllum's, of which Myriophyllum species are present in the lake, but were not observed in the seedbank. Therefore some active planting would probably be required for rehabilitation.

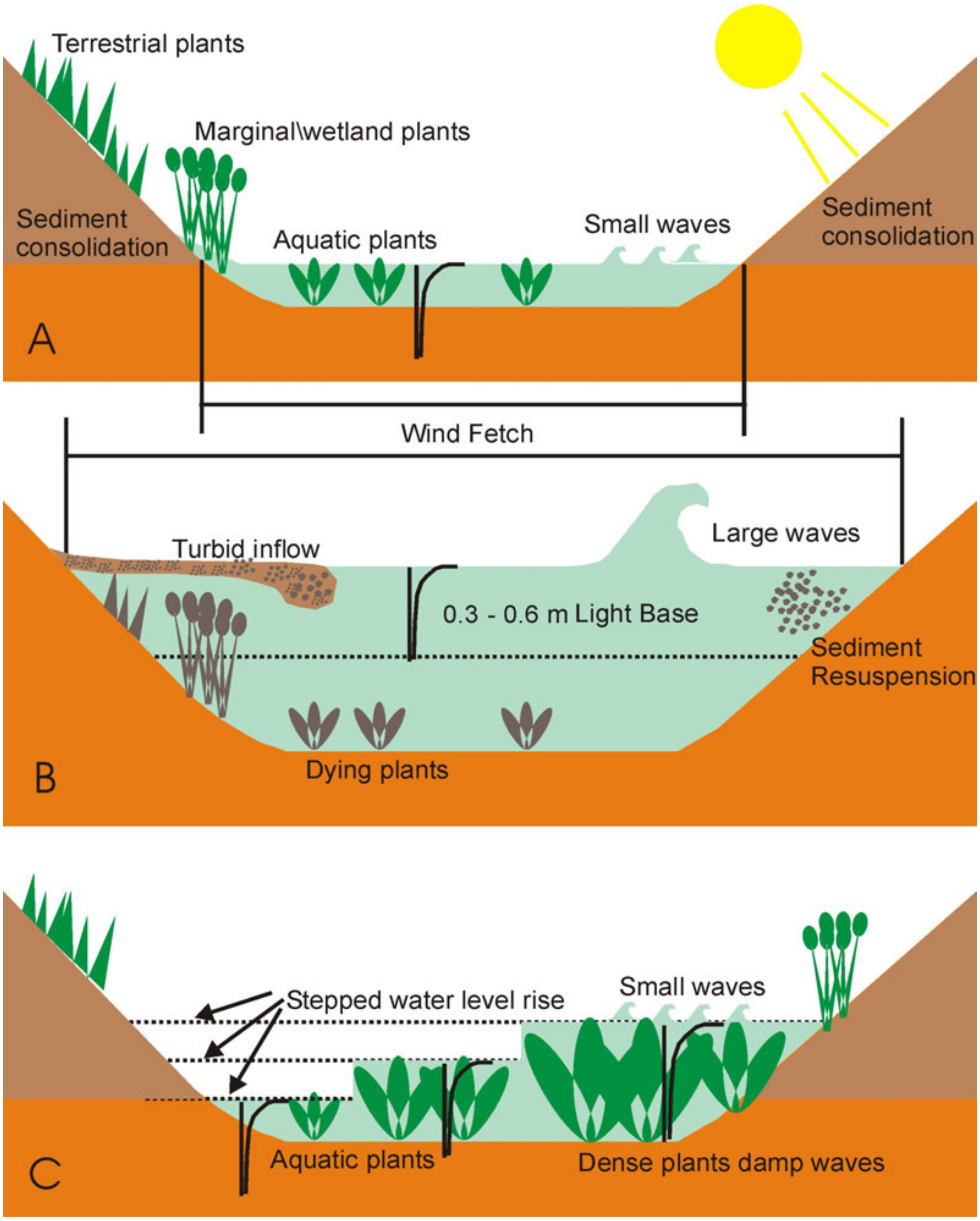

Figure 25: Schematic of Lake Waikare illustrating the consequences of water level reinstatement following drawdown: A) the potential benefits of lake drawdown including sediment consolidation, reduction of wave stress through reduced wind fetch, and bringing the sediment surface into the light penetration zone to allow plants to grow. B) The consequences of rapid water level reinstatement following drawdown; aquatic plant density is insufficient to damp waves allowing sediment resuspension and consequent low light penetration, so establishing aquatic plants are

robbed of light and die. Turbid inflows may also occur during floods. C) Water level is raised in small steps, allowing aquatic vegetation to maintain contact with the good light climate near the water surface, and grow dense enough to withstand and damp wave action before large wind fetches (and potentially large waves) are reinstated.

Our conclusion based on the present study and that of Reeves et al. (2002) is that lake drawdown does not provide the sole answer for the rehabilitation of Lake Waikare. The study has demonstrated that drawdown does hold some benefits for the lake, and should form part of the rehabilitation process if ever it were to be attempted. But it is our opinion that the number and scale of the problems the lake suffers (e.g. koi carp, large wind-wave fetch, hyper-eutrophic) make it a poor candidate for rehabilitation.

The study has shown the benefits of temporary sediment exposure to the establishment of plants. There is no reason that these benefits could not be gained in a small area around the lake margins, by a small modification to the current fixed water level management regime. By oscillating the water level by $\pm$0.2 m (half the median light base) around the present fixed water level, marginal/wetland vegetation (tolerant to wetting and drying) could be encouraged in the lake margins, possibly restoring some natural habitat.

If future investigation is to be undertaken, then wave baffles could be used to study the relationship between the wave environment and the establishment and persistence of plants. The impact of pest fish on vegetation and methods of controlling pest fish could be assessed.

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7 Glossary

Desiccation – the process of drying out.

Drawdown – reducing water levels in Lake Waikare.

Clarity – the clarity of water is related to how efficiently light is transmitted through the water body The greater the proportion of photons transmitted unabsorbed and undeviated in their path by scattering, the greater the clarity. There are two main aspects of water clarity:

1. Sighting distance through water (*visual clarity*).

2. Penetration of diffuse irradiance from the sun into water (*light penetration*).

These two aspects of clarity are not equivalent, a water body can have high light penetration but low visual clarity (Davies-Colley, 1993).

Light penetration – penetration of diffuse irradiance from the sun into water, referred to colloquially as the "light climate" in this report.

Visual clarity – sighting distance through water.

Turbidity – "cloudiness" of the water body resulting from deflection (side-scattering) of photons off particles suspended in the water body. Turbidity is strongly inversely correlated with visual clarity, but NOT to light penetration for plant-growth. Turbidity is an *index* of water clarity but not a *measure*, due to the following reasons:

1. Turbidity is measured by nephelometry and is highly instrument specific.

2. Turbidity measurement may suffer interference from adsorption, or sources of scattering other than particulates, such as bubbles.

3. Turbidity is an arbitrary, relative scattering measurement, which does not relate simply to scattering in absolute units, to optical concerns such as water clarity, or to suspended solids concentration (Davies-Colley, 1993).

Appendix 1 – Laboratory analysis techniques

Parameter	Description	Detection Limit	Method
Electrical Conductivity(EC)	Electrical Conductivity meter, measured at 25°C	0.01	APHA 2510B
pH measurement(pH)	Laboratory pH meter and probe	0.1	APHA 4500H
Inorganic Suspended Solids(Inorg SS)	Filtration, drying at 104 C, followed by furnacing at 400 C	0.5	APHA 2540D
Volatile Suspended Solids(VSS)	Filtration, drying at 104 C, followed by furnacing at 400 C	0.5	APHA 2540D
Suspended Solids(SS)	Filtration, drying at 104 C, followed by furnacing at 400 C	0.5	APHA 2540D
Total Organic Carbon(TOC)	Total Organic Carbon Analyser	0.2	APHA 5310 B
Nitrate + Nitrite Nitrogen(NO3-N)	DRP,NH4-N,NO3-N, flow injection analyser	1	Lachat
Ammonium Nitrogen(NH4-N)	DRP,NH4-N,NO3-N, flow injection analyser	1	Lachat
Dissolved Reactive Phosphorus(DRP)	DRP,NH4-N,NO3-N, flow injection analyser	1	Lachat
Total Nitrogen(TN)	Persulphate digest, auto cadmium reduction, FIA	10	Lachat
Total Phosphorus(TP)	Acid persulphate digestion, molybdenum blue colorimetry.	1	NWASCO 38
% Moisture in Sediment	Sediment dried at 104°C, moisture loss calculated	0.1	In House
Particulate Phosphorus(PartP)	Acid digest, NH4-N and DRP auto analysis	0.1	Searle
Particulate Nitrogen(PartN)	Acid digest, NH4-N and DRP auto analysis	0.1	Searle
Particulate Carbon(PC)	Catalytic comb @900°C, sep, TCD, CE Instruments C/N analyser	0.01	MAM, 01-1090
Particulate Nitrogen(PN)	Catalytic comb @900°C, sep, TCD, CE Instruments C/N analyser	0.02	MAM, 01-1090
Particulate Organic Carbon(POC)	Catalytic comb @900°C, sep, TCD, CE Instruments C/N analyser	0.01	MAM, 01-1090
Particulate Organic Nitrogen(PON)	Catalytic comb @900°C, sep, TCD, CE Instruments C/N analyser	0.02	MAM, 01-1090
Density	Measured volume of sediment/water mixture is weighed	0.01	In House
Electrical Conductivity(EC)	Electrical Conductivity meter, measured at 25°C	0.01	APHA 2510B

Appendix 2 – List of collection sites, depths and GPS references for seed bank cores.

Site	Depth	Site description	GPS	Cores (1-4)
1	0.4	At extreme lake edge, willows and swamp cypress	2702547E 6418699N	Y
1	1.0	100 m off point	2702592E 6418674N	Q
1	1.3	200 m off point planted with weeping willows	2702657E 6418645N	O
2	0.4	Pasture to edge, clay reefs and sand	2702216E 6418945N	N
2	1.0	c. 50 m of shore, soft sediment	2702169E 6418881N	X
2	1.3	Well out into the lake	2702208E 6418471N	Z
3	0.3	Willows fringing pasture	2701473E 6418291N	GG
3	1.0	c. 500 m from shore	2701665E 6418503N	HH
3	1.3	Close to deep site 2	2702123E 6418425N	AA
4	0.3	Adjacent to major ditch to right of bay, willow and reed	2701480E 6417792N	FF
4	1.0	c. 150 m offshore, just outside islands	2701840E 6418005N	EE
4	1.3	Close to deep 3	2702148E 6418266N	V
5	0.4	At shore, soft over hard pan	2701770E 6416819N	BB
5	1.0	c. 300 m offshore of bay	2702309E 6417374N	CC
5	1.3	c. 500 m offshore of bay	2702414E 6417649N	DD
6	0.3	At shore in bay by Te Onetea Stream, willows	2702009E 6415688N	MM
6	1.0	c. 200 m offshore	2702137E 6415757N	NN
6	1.3	c. 500 m offshore	2702363E 6415919N	OO
7	0.3	Inside of bay at shore amongst willows	2702346E 6415242N	KK
7	1.0	c. 100 m offshore	2702421E 6415325N	LL
7	1.3	c. 460 m offshore	2702529E 6415437N	II
8	0.4	Up drain, quite open to lake	2702904E 6413755N	QQ
8	1.0	c. 150 m offshore, willow scrub	2702867E 6413914N	SS
8	1.3	c. 500 m offshore	2702892E 6414350N	JJ
9	0.6	At edge of big island, lee side, toi-toi and scrub	2703707E 6414409N	PP
9	1.0	10-20 m from big island, rough uneven bottom, clay	2703720E 6414408N	RR
9	1.3	20 m from smaller of two islands	2703674E 6414753N	P
10	0.3	Close to shore, toi-toi fringe	2704248E 6414022N	W
10	1.3	Inshore of large island. Fibrous, hard, lumpy sediment	2704205E 6414137N	S
10	0.9-1.1	Lumpy, hard bottom	2204233E 6414062N	T

Site	Depth	Site description	GPS	Cores (1-4)
11	0.3	Sandy, lake edge with reeds and grass	2705573E 6414694N	U
11	1.0	Sandy, firm bottom	2705472E 6414698N	R
11	1.3	c. 100 m from shore, fibrous, hard sediment	2705346E 6414687N	G
12	0.4	In bay next to open reeds and rushes	2705985E 6414477N	I
12	1.0	In beside island, exposed.	2706179E 6414128N	H
12	1.3	c. 500 m off shore	2706243E 6413724N	J
13	0.4	Around corner from Swamp Cypress	2704743E 6413380N	M
13	1.0	Out towards island	2704938E 6413197N	L
13	1.3	Out towards island	2705358E 6412920N	K
14	0.4	Under willows, near Black Lake outlet	2704335E 6412026N	A
14	1.0	Near Islands and Black Lake outlet	2704520E 6412063N	B
14	1.3	300 m out in lake near deep 15 site	2705034E 6412333N	C
15	0.3	Pasture, rushes, no drains, some pines	2705927E 6411900N	D
15	1.0	Soft mud	2705912E 6411982N	E
15	1.3	Soft mud, c. 300 m from shore	2705817E 6412098N	F

Appendix 2 – Observations on sediment type and alterations by drying.

Site	Depth	Cores	Substrate
1	0.4	Y	Sandy, firm, little shrinkage, slight crust
1	1.0	Q	Firm to soft, little shrinkage, slight crust, some fine sand
1	1.3	O	Shrunk by 1/2 to 2/3, firm to hard, some cracks
2	0.4	N	Firm to soft, sand and organic, slight crust
2	1.0	X	Firm, sandy, shrunk by 3/4, slight crust
2	1.3	Z	Hard, shrunk by 1/2
3	0.3	GG	Fine, soft, slight crust, little shrinkage
3	1.0	HH	Some shrinkage, sandy, slight crust
3	1.3	AA	Firm, shrunk by 2/3
4	0.3	FF	Firm to soft, some sand, little shrinkage
4	1.0	EE	Fine sand, slight crust, little shrinkage
4	1.3	V	Firm, shrunk by 2/3
5	0.4	BB	Firm, sandy
5	1.0	CC	Firm, sandy, slight crust
5	1.3	DD	Firm to soft, sandy, slight crust
6	0.3	MM	Sandy, no shrinkage
6	1.0	NN	Firm to soft, fine sand, slight crust
6	1.3	OO	Firm to soft, slight shrunk by 3/4th, slight crust
7	0.3	KK	Soft, sandy, no shrinkage
7	1.0	LL	Sandy, slight, soft crust
7	1.3	II	Hard to firm, shrunk by 2/3
8	0.4	QQ	Firm, fine, but some pumice, fibrous, slight crust
8	1.0	SS	Hard to firm, shrunk by 2/3 to 3/4
8	1.3	JJ	Hard, shrunk by1/2 to 2/3, cracked
9	0.6	PP	Firm to soft, fine sand and wood debris
9	1.0	RR	Firm, shrunk by 2/3 to 3/4, crusty
9	1.3	P	Firm to soft, clay and pumice/wood, uneven surface, crust
10	0.3	W	Firm, sand and fine clay
10	1.3	S	Firm, organic to woody/fibrous, crusty-uneven
10	0.9-1.1	T	Firm to soft, shrunk by 3/4, some woody/fibrous
11	0.3	U	Firm to soft, fine organic and sand, slight crust
11	1.0	R	Firm, some black organic and fine sand,
11	1.3	G	Woody/fibrous over firm, some shrinkage and crust
12	0.4	I	Firm, shrunk by <2/3
12	1.0	H	Hard to firm, shrunk by 1/2 to 2/3rds
12	1.3	J	Hard, shrunk by 1/2

Site	Depth	Cores	Substrate
13	0.4	M	Firm, slight shrinkage by 3/4, sandy, slight crust
13	1.0	L	Hard, shrunk by 2/3, some cracks
13	1.3	K	Hard, shrunk by 2/3, some cracks
14	0.4	A	Firm, fine, organic crust
14	1.0	B	Hard to firm, shrunk by 1/2 to 2/3rds
14	1.3	C	Very hard, shrunk by 1/2
15	0.3	D	Fine, sandy, slight crust
15	1.0	E	Firm to soft, shrunk by 2/3 to 3/4, slight crust
15	1.3	F	Hard, shrunk by 1/2 to 2/3, cracked